K. GLADKOV

THE ATOM FROM A TO Z

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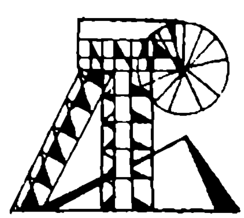
ATOMIC ENERGY AND MANKIND

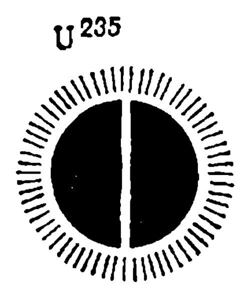
Scientists have calculated that an able-bodied man working a whole year eight hours a day without weekends can produce at most 250 kilowatt-hours of energy. To obtain the same amount of electrical energy one must, say, burn about 125 kilograms of coal in the furnace of a modern electric power station.

In 1980 Soviet industry is to produce three million millions of kilowatt-hours of electrical energy, one and a half times the amount produced by all countries of the world to-day! If we divide the three million millions of kilowatt-hours by 300 million people (the expected population of the USSR by 1980), the share of each citizen will be ten thousand kilowatt-hours.

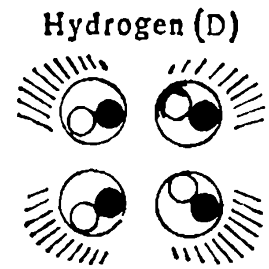
250 kWh per year



1 kg=11.6 kWh



1 kg=22.9 mil. kWh



1 kg=117.5 mil. kWh

This, of course, is a lot, especially if we recall that we had 14 kilowatt-hours per capita in 1913 and three kilowatt-hours in 1920. But what is a dream to-day will seem an infinitesimally small figure at the end of this century.

We are striving to reconstruct the face of the Earth. Ri-

vers flowing to the unpopulated northern regions must be reversed, the gigantic surpluses of water in Siberian rivers diverted to deserts of Central Asia, the original level of the Caspian sea restored, new rivers and seas created.

This will be followed by virtually gigantic work. Ocean currents will be diverted to bring warm climate to entire continents. Deserts will be turned into blooming gardens, the planet will regain its former green mantle. The tundras will become warm, permafrost will disappear. The words "crop failure", "poverty", "hunger" will be stricken out of all languages. Man will penetrate into the depths of the earth, into its inexhaustible storage room of mineral wealth. The world's oceans will be turned into an everlasting source of food and industrial raw materials, artificial islands and whole continents will emerge from its vast expanses. Numerous Earth satellites will be built, the Moon and the nearest planets will be populated ... .

Any of these great deeds will require, in the first place, tremendous expenditures of energy—tens, hundreds (and later thousands) of millions of millions of kilowatt-hours. And with further development of civilization more and more energy will be needed.... A whole ocean of it!

People are naturally beginning to wonder whether the existing power sources will last long, whether we shall not have power famine even at the end of this century, mainly because the reserves of fossil fuels—coal, petroleum, natural gas, peat, oil shales, firewood—will be exhausted. What resources are available to-day, what awaits us in the near and far-off future?

We are now witnessing a breath-taking race in building power giants. Hydroelectric stations of literally astronomic

power rating are being commissioned one after another: the Lenin Station on the Volga—2.1 million kilowatts, the 22nd CPSU-Congress Station on the Volga—2.3 million kilowatts, the Bratsk Station—3.6 million kilowatts. The Krasnoyarsk giant rated at 5 million kilowatts is under construction. One such station generates several times the amount of power envisaged by the First Soviet Plan for the whole country! The construction of still more powerful hydroelectric stations on the rivers Angara, Yenisei, Lena and others is being projected. All the rivers of the USSR taken together could yield about 250 million kilowatts, three times the amount produced by all the electric power stations of the country in 1960. This is a very imposing figure indeed, but it falls short of our future needs.

So far coal is the most common power source in the whole world, since its share in the mineral wealth of the Earth is the greatest.

The proved reserves of petroleum on the globe are just one per cent of those of coal. Considering, however, that it is much easier, much more convenient and less costly to produce, transport and use petroleum as compared to coal, petroleum production and consumption have not only overtaken, but are beginning to outstrip those of coal. In 1968 over 1,915 million tons of petroleum was produced in the whole world. The production of natural gas is growing at the same or even greater rate.

The abrupt increase in the production of coal and particularly of petroleum and gas, in turn, makes it possible to speed up the construction and commissioning of super-power thermal electric stations.

Electric power will long remain the ideal, predominant

form of energy which mankind will use in all branches of its production activity. But it has its own inherent weaknesses.

Thermal energy, for instance, can be stored, accumulated (though indirectly) in the form of reserves of fuel, combustible and explosive materials or chemicals. Electrical energy cannot be stored or accumulated, directly or indirectly, except in negligible amounts. It has to be consumed immediately it is produced.

Well then, what should be done if sources of energy accumulated as fuel or falling water are nonexistent or inadequate? For instance, about 80 per cent of the industry and population of the USSR is concentrated in the European part of the country and in the Urals, whereas the predominant part of the power resources, water and fuel are located in the eastern and north-eastern regions of the country. What would be the quickest and most economical and technically rational way of solving this problem? Or tackling another, more remote problem of collecting the electrical energy produced by the whole country—tens of millions of kilowatts—into an "electric fist" of tremendous power? But this energy cannot be loaded on a rocket and used for a space flight. It cannot be stored, charged into something, condensed or compressed. And the conventional multi-step units and machines for the transformation of fuel energy into electric power are extremely bulky and inefficient.

Therefore the scientists had long been dreaming of a source which, while negligibly small in size, would possess a fantastic amount of energy exceeding that of the most powerful explosives available.

And then a miracle happened. Thirty grams of uranium-235

proved to be quite sufficient to feed for twenty-four hours a 5,000-kilowatt electric power station which usually burned about one hundred tons of coal per day. And a few hundred grams of this remarkable material enables the engines of the world's most powerful Soviet icebreaker *Lenin* to develop 44,000 horsepower!

Nature has concealed stupendous amounts of energy in a negligibly small volume of matter—the atomic nucleus. But man has been able to open thousands of most intricate locks guarding the heart of the atom, and harness nuclear energy.

And although more than 20 years have elapsed from the date of this great discovery, about which the prominent French physicist Paul Langevin said that as regards its importance in the history of civilization it can be placed along with the discovery of fire, not only the layman, but also the scientists dealing with this new type of force, cannot even now get used to such an "unnatural" discord between the tiny amounts of matter and the vast amount of energy it contains.

To think that a kilogram of petroleum, which is the best of all fuels, yields only 11.6 kilowatt-hours of thermal energy when burned completely, whereas the amount of energy released in the fission of atomic nuclei of uranium-235 is 22.9 million kilowatt-hours, almost two million times as much! This energy can be liberated either all at once, in the form of an explosion of colossal destructive force lasting only one-millionth of a second (an atomic bomb), or produced gradually, as is done in a conventional electric power station.

Still more energy is liberated in a so-called thermonuclear

reaction—the fusion of atomic nuclei of light elements, for instance, hydrogen. The amount of energy obtained in this reaction reaches a still more incredible figure—117.5 million kilowatt-hours per kilogram of hydrogen! And finally, what seems to be a fantasy entirely beyond human understanding—matter has proved to be a store-house of fabulous amounts of energy, a "spring" of astronomic dimensions which could, if ever released, extract 25 thousand millions of kilowatt-hours of energy from one kilogram of a substance, which is equal to the annual yield of all the gigantic hydroelectric stations on the Volga taken together! Recall that the people and all things that surround them consist of millions of millions of millions of millions of atoms whose "springs" were "wound up" at the time when all the substances around us, the whole planet, the Solar system, the Galaxy, the entire Universe were being formed in the infinity of Cosmos.

At present the thermonuclear reaction can be realized only in the form of an explosion of monstrous force—an explosion of a hydrogen bomb. The day the scientists learn to control the thermonuclear reaction man will become the real master of nature because he will be in possession of virtually unlimited and inexhaustible power resources.

The fissionable materials in the earth's crust are not so numerous, and they are bound to disappear altogether, since our planet will continue to exist just for another few tens of thousands of millions of years. As to hydrogen, its reserves on Earth are tremendous: hundreds of millions of cubic kilometres of water in the oceans, rivers, lakes, ground waters, atmospheric moisture, tens of millions of cubic kilometres of ice in the Arctic and Antarctic. It will last

quite a long time, even if we think in terms of epochs and eras.

The colossal concentration of controlled energy in a negligibly small volume will enable man to send rockets into space—to the most remote planets, into other stellar worlds and, possibly, into neighbouring galaxies, to realize (somewhere in the very distant future) the fantastic attempt at changing the angle of inclination of the Earth's axis, thereby turning our planet into an eternal thriving Paradise or, say, transfer it to the orbit of some other star.

SYMBOLS AND DEFINITIONS

In nuclear physics the chemical elements are denoted by the same letters as in chemistry. But along with the Latin abbreviation, two figures are placed: at the right-hand top the atomic weight of the element corresponding to the total number of nucleons (protons and neutrons) in the atomic nucleus, and at the left-hand bottom the atomic number of the element in Mendeleyev's Periodic Table which denotes the number of positive charges (protons) in the nucleus and the corresponding number of electrons in all the orbits. For instance, lithium, $_3Li^7$. The atomic number 3 of the element at the left-hand bottom means that the nucleus contains three positively charged protons, and three electrons rotate in orbits around the nucleus. At the right-hand top is the atomic weight 7. By subtracting 3 from 7 one can find the number of neutrons in the nucleus, which is 4.

For simplicity, the atomic number is often omitted (polonium-210, radium-226, uranium-238, and so on, or Po^{210}, Ra^{226}, U^{238}).

Atomic particles also have their symbols:

e^-=electron. The minus at the right-hand top is the negative sign of the elementary electric charge;

e^+=positron. The plus at the right-hand top is the positive sign of the elementary electric charge;

$_0n^1$=neutron. The unity at the right-hand top is the atomic weight of the nucleon, and the zero at the left-hand bottom signifies the absence of an electric charge.

Velocity. If a body or particle moving in space displaces by equal distances within equal intervals of time, it is said

to have a constant velocity. The unit of velocity in the metric system is one centimetre per second (cm/sec).

Acceleration. Linear acceleration is the rate of increase of velocity with time expressed in cm/sec^2.

Force. Any action which alters or tends to alter a body's state of rest or of uniform motion in a straight line. A force is equal to the product of the mass of the body by its acceleration. The unit of force is the *dyne*. One dyne is a force which, acting on a body of mass 1 gram speeds it up by one unit of acceleration ($1\ cm/sec^2$).

Work. When a body offering resistance to a force moves with an acceleration or rises to a certain height under the action of this force, it is said that the force performs definite work. The unit of work is the work done by a force of 1 dyne over a distance of 1 cm. This unit is called the *erg*. The practical unit of work is the *joule* (*j*), which is equal to 10^7 ergs.

Power. The amount of work done in a unit of time. The physical unit of power is 1 erg/sec, and the practical unit 1 joule/sec, which is also called the *watt* (*W*). One thousand watts makes a *kilowatt* (*kW*).

Energy. Work corresponding to a definite power developed within a second may be continued for hours, days, years. This depends on the amount of energy spent on this work. The energy required for developing a power of 1 kW within an hour is equal to one *kilowatt-hour* (*kWh*).

In most cases energy is obtained by burning such fuels as coal, petroleum, wood, peat, nuclear fuel. Heat is usually measured in *calories (cal)*. One calorie is the heat necessary to raise the temperature of 1 g of water by 1 °C. A thousand calories, or one *kilocalorie* (*kcal*), can raise the tempera-

ture of 1 kg of water by 1°C. The burning of 1 g of coal yields 8 kcal, petroleum—12, natural gas—10.6, and wood—4 kcal of heat. One kilowatt-hour is equal to 860 kcal.

Kinetic energy. The energy of motion of any material body or particle, or the amount of work which a body is capable of performing due to its motion. Kinetic energy is equal to half the product of the mass of a body by the square of its velocity. The kinetic energy of a set of material bodies is equal to the sum of the kinetic energies of each body taken separately.

Electron-volt, eV. The charge of an electron is a strictly constant value. When an electron enters an electric field set up by the difference of potentials of 1 volt between charged particles, it is accelerated to a velocity of 593 km/sec. Its kinetic *energy* naturally increases with velocity. The kinetic energy of an electron is equal to the product of its charge by the difference of potentials, i.e., at the indicated velocity it will be 1.6×10^{-12} erg, or 1.6×10^{-19} joule. This quantity of energy corresponds to one *electron-volt* (*eV*).

To give you an idea about the practical magnitude of this unit, the average energy of thermal motion of gas atoms or molecules, and also the energy of atoms of a solid or liquid at room temperature is equal to about 0.03 eV.

The energy of an electron in the highest energy state within an atom of hydrogen (in the outermost orbit) is 13.53 eV. An electron which has acquired an energy exceeding this value leaves the atom for ever.

The energy of all other—charged and uncharged—moving particles and also photons is measured in electron-volts as well.

Potential energy. Work which a body is capable of performing by virtue of its position or state (for instance, a compressed spring, a load raised to a great height, a store of fuel, etc.), or work which must be applied to a body to displace it in a direction opposite to that of a latent (potential) force, which depends only on the position of the body.

Joule, j. The absolute joule is a unit of work done per second by a current of one ampere passing through a 1-ohm resistance. The International joule is equal to 1.00019 absolute joule. In terms of units of power 1 joule per second is equal to 1 watt.

Oersted, oe. The physical properties of the space around a magnet differ from those of the space where the magnetic forces do not manifest themselves. A space where magnetic forces manifest themselves is generally said to contain a magnetic field. This field is characterized, at a point, by a quantity called the *magnetic field intensity* or *strength.* The unit of magnetic field intensity is the *oersted*, named after the Danish physicist Hans Christian Oersted, who discovered on the 15th of February, 1820, the magnetic effect of an electric current. Oersted noticed that the needle of a magnetic compass placed near a wire conductor deflected each time the current was switched on and off. An electric current gave rise to magnetism. A few days later, the French scientists Arago and Ampere designed a solenoid—a coil of insulated wire. By passing a current through this wire one could obtain exactly the same kind of a magnetic field as that produced by permanent magnets.

Artificial magnets made at present have colossal field intensities reaching hundreds of thousands and even millions of oersteds. (The intensity of the Earth's magnetic field is

below 1 oersted.) Such magnets are extensively used for research into a wide range of magnetic phenomena, for obtaining extremely low temperatures, for analysis of nuclear particles in mass-spectrometers, Wilson cloud chambers, bubble chambers and other ionization chambers, for investigation of elementary particles in all types of accelerators and in a multitude of other physical and technical devices, and also for studying the phenomenon of superconductivity in metals.

A

Alpha-particles (alpha-rays). Marie Curie (Marja Sklodowska) and Pierre Curie, who at the time did not know anything about the nature of the three types of newly discovered (in 1896) rays emitted by radioactive substances, named them after the first letters of the Greek alphabet: *alpha-*, *beta-*, and *gamma-rays*. Somewhat later it was established that beta-rays are nothing else than a flux of negatively charged particles—electrons, gamma-rays are electromagnetic radiation of still shorter wavelength than the famous Röntgen rays (X-rays) discovered the year before, and alpha-rays are atomic nuclei of helium ($_2He^4$) consisting of two protons and two neutrons. The positive electric charge of such a nucleus is in absolute value twice the negative charge of the electron and its atomic weight is 4.004. The mass of the alpha-particle is 6.664×10^{-24} g.
An alpha-particle accelerated to high energies is a more efficient missile of the "atomic artillery" than the proton, since, although it carries a double positive electric charge, it is four, and not two times as heavy as the proton.
Angström, A. A unit of length used for measuring electromagnetic oscillations of very short wavelength: infra-red, visible light, ultra-violet, X-, and gamma-rays. One Angström is equal to a one hundred-millionth of a centimetre (1×10^{-8} cm). It is widely used in optics and in atomic and nuclear physics. For instance, the length of the visible spectrum of light waves lies between 4,000 and 8,000 A.
Annihilation (from the Latin "self-destruction"). The miraculous world of elementary particles, of which about

40 have been discovered so far, possesses a still more amazing property· each of these particles has its own *antiparticle*, which has the same mass and magnitude of charge as a particle, but a charge of opposite sign. The most striking point is that a particle and its antiparticle, when coming into collision, immediately "annihilate" each other, i.e., cease to exist, giving rise either to other elementary particles or to radiation quanta. The process obeys all laws of physics, including the laws of conservation of energy and of momentum. Only the energy and mass of the newly-formed particles change. Thus, when a free electron (*negatron*) encounters its antiparticle, a *positron*, annihilation usually results in two *photons (gamma-quanta)*, which, taken together, possess the energy and momentum of the collided pair (see the picture on p. 29).

Under certain conditions a gamma-quantum can be transformed into an electron-positron pair.

Antimatter. After antiparticles had been discovered and their existence confirmed experimentally, the question naturally arose whether there are such atoms in nature whose nuclei are made up not of protons, but of antiprotons, and whose shells are formed not of electrons, but of positrons. In this case nothing would change in principle. Simply such "transformed" atoms, for instance those of hydrogen, would be called antihydrogen, and the matter consisting of them, antimatter. Proceeding from the property of symmetry, which exists everywhere in nature, one may assume that at least half of the atoms in the Universe should represent such antimatter! If, however, antimatter existed on Earth or even in our Galaxy, it could not exist for long and would rather soon annihilate with ordinary matter

with a release of energy a thousand times the amount of energy liberated in a hydrogen bomb explosion. It is not yet known whether antimatter exists in other worlds out in space, although theoretically it is not improbable.

Antiparticles. Of the rather large number of the elementary particles discovered to date, 30 may be divided into 15 pairs.

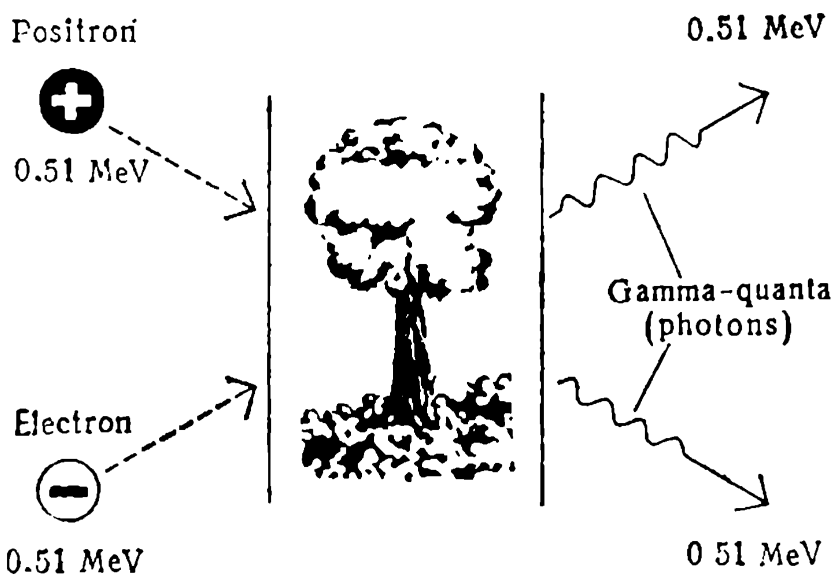
The masses of the particles of each such pair, for instance, proton-antiproton, electron-positron, neutron-antineutron, etc., are precisely the same, whereas their electric charges (with the exception of neutral particles) and physical properties are opposite.

When the two particles of any such pair collide, they immediately annihilate each other. Two photons appear in their place, that is, the energy latent in the rest mass of these particles transforms into the energy of radiation particles which have no rest mass.

Only the photon and the neutral mu-meson (μ-meson, muon) have no antiparticles and are taken to be identical to their antiparticles.

The first antiparticle which became known to man was the *positron*, which was discovered in 1933, although its existence had been predicted much earlier. The positron, or positive electron, has the same mass and magnitude of charge as the electron, but a charge of opposite sign. On colliding, a positron and an electron immediately annihilate each other, giving rise to two photons with an energy of 0.51 million electron-volts (MeV) each, the total energy of the resulting two photons being equivalent to the double rest mass of the electron. A positron emerges as a result of a process called *pair production*. This process consists

in that a high-energy photon, colliding with atomic nuclei of heavy elements, such as lead, knocks out of them a pair of oppositely charged particles—an electron and a positron. The minimum energy of a photon necessary to produce such a pair is 1.02 MeV (0.51 MeV per each particle). This is one of the numerous examples of direct transformation of energy into rest mass. An electron and a positron may



emerge in beta decay. But here a neutrino is always produced alongside the positron.

The *antiproton* (or negative proton) is similar to the proton except that it carries an equal negative charge. It can be produced by bombarding a substance with protons of kinetic energy not less than 6 thousand million electron-volts (6 GeV). This energy converts directly into a rest mass and the kinetic energy of the proton-antiproton pair. In 1956 the antineutron was discovered. Since the neutron has no charge, the antineutron should also be neutral. Ho-

wever, when an antineutron encounters either a neutron or a proton, they annihilate each other.
The products of annihilation of nucleon antiparticles (i.e., a proton and antiproton, a neutron and antineutron) are usually *pi-mesons* (*π-mesons*, *pions*).
Atom. The main character of this book and of the whole material world surrounding us.
The idea that the entire infinite variety of substances in nature consists of negligibly small and invisible particles which cannot be subjected to further division occurred even to the sages of ancient Orient, India, China, and Greece. But all this was the result of contemplation, speculation and conjectures, sometimes even brilliant ones, but not of experiments or scientific generalizations. This conjecture was stated most comprehensively by the Greek philosopher Leukippos and his disciple Democritus, who lived in the sixth century B.C. Democritus invented the term "atom" (from the Greek word "atomos" meaning indivisible). These two great thinkers of the ancient world, to whose names we might add those of Epicurus, and Lucretius Carus, laid the foundation of the materialistic understanding of natural phenomena—the philosophical theory of the eternity of matter, its non-creation, indestructibility, and the eternal cycle of nature.
But it was only after a lapse of 17 centuries that these conjectures of the ancient scientists were translated into the language of true science by the great Russian scientist M. Lomonosov. The theory of structure of matter proposed by him was based on the existence of "corpuscles" (particles)—atoms. The entire motion of matter—taught Lomonosov—amounts to the motion of atoms and is the cause

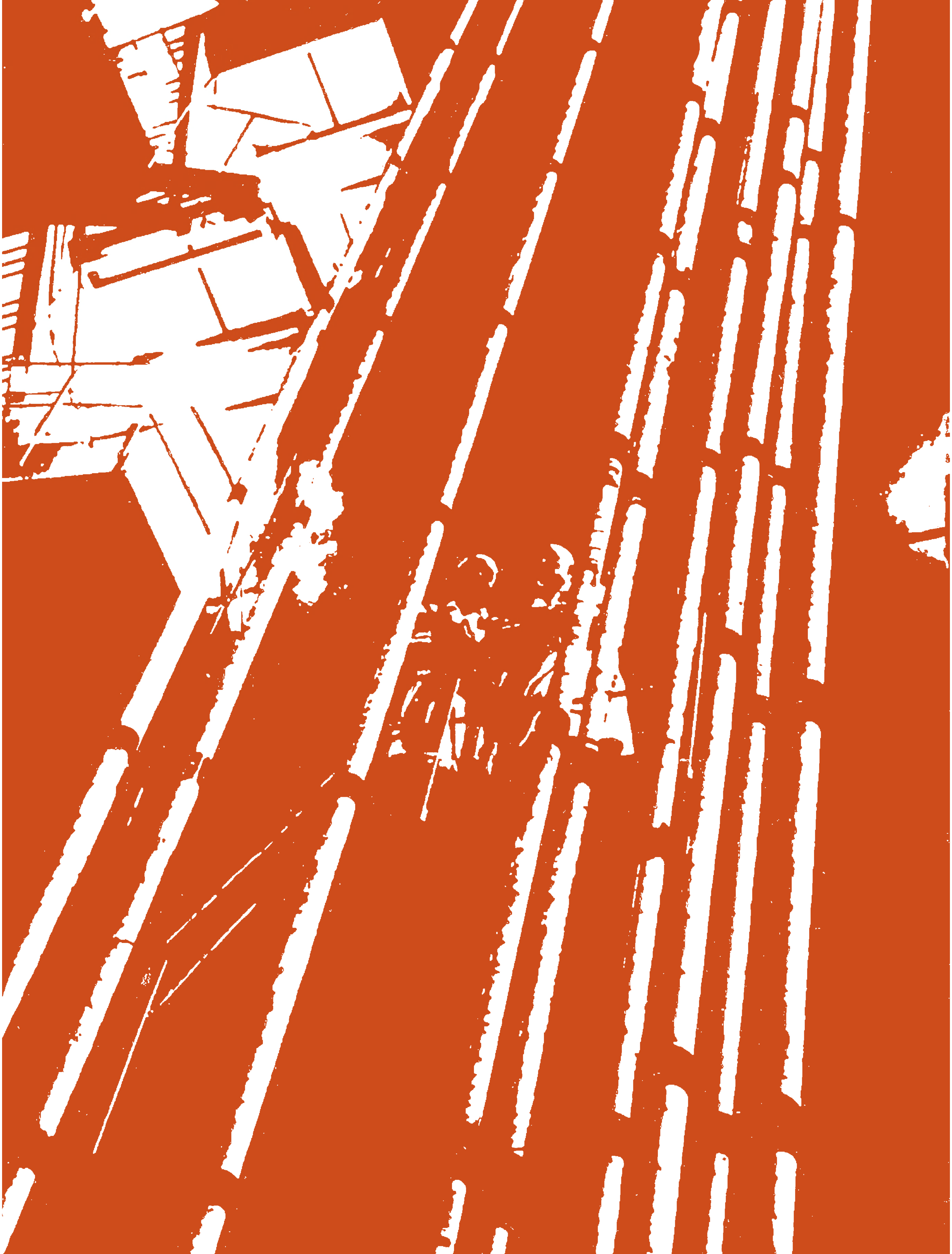
of all changes in nature. The motion of atoms in a substance also determines the degree of its heat, or its temperature. At the same time Lomonosov predicted the existence of the lowest possible temperature—absolute zero, at which the thermal motion of the particles ceases altogether.

The tiniest portion of any substance of the surrounding world which still completely retains all the properties of this substance was named the *molecule*. When decomposed, a molecule of a substance ceases to exist independently and breaks up into *atoms*, the smallest particles of which all chemical elements are made.

Studying step by step the diverse natural substances and discovering new elements, the chemists established their distinguishing features with ever-growing precision. In the course of this meticulous and time-consuming study many surprising and even incomprehensible things were revealed. The atoms of some elements were extremely light, while those of others were extremely heavy. Some elements reacted with each other so vigorously that they had to be kept separately. Conversely, other elements could not be made to react under any conditions.

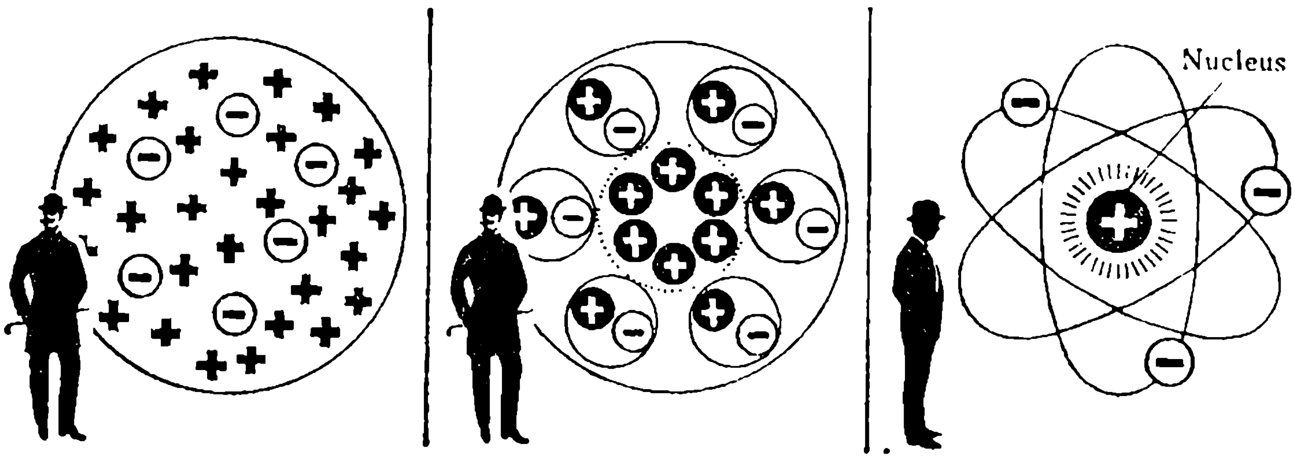
All this could not but stir the minds of the scientists. Now and again they guessed in the chaotic disorder of facts some regularities testifying to the existence of a certain strict, but yet unknown order. The seeming chaos evidently existed not in nature, but in the fragmentary, incomplete knowledge of the scientists. That was where order had to be established in the first place. The credit for revealing the complicated and carefully guarded secrets of nature goes to the prominent Russian scientist Dmitri Ivanovich Mendeleyev, Professor of Chemistry at the Technological Insti-

titute in St. Petersburg (see *Mendeleyev's Periodic Table of Elements*).
The conjecture about the finiteness of the atom lasted for over a thousand years. And it took just a few decades to establish conclusively that the indivisibility of the atom had been a delusion; true enough, it reflected the general idea of the ancient materialist philosophers concerning the indivisibility of the basic elements of matter.
It was found that the atoms of the chemical elements are not atoms at all, but whole peculiar and relatively vast worlds built up of simpler components—*particles*. And though the scientists named them "elementary" (simple) particles, the whole course of development of modern science indicates that they are far from elementary (see *Elementary Particles*).
The primary and basic conclusion was that the atom consists of two principal parts—a heavy and positively charged nucleus (see *Nucleus, atomic*) in which almost the whole mass of the atom is concentrated, and a light shell made up of atoms of electricity—electrons (see *Electron—"the atom of electricity"*). The electrons rotate about the nucleus with a tremendous velocity, but never fall on it. The diameter of the atom is approximately one hundred-millionth of a centimetre (10^{-8} cm), and that of its nucleus, about one ten-thousandth or one hundred-thousandth that of the atom.
The atom of the lightest element in nature—hydrogen—consists of two particles: a nucleus, whose mass is $1.6724\times\times10^{-24}$ g, and a single electron rotating around it, whose mass is 9.1085×10^{-28} g, about 1/1836 of the mass of the nucleus of the hydrogen atom. In helium, which follows hydrogen in the Periodic Table, two electrons rotate about



the nucleus, in lithium three, in oxygen 8, in iron 26, and in uranium 92 electrons. To simplify calculations, the mass of all atoms of chemical elements is usually expressed in arbitrary units (see *Atomic weight*) as related to 1/16th of the mass of the principal oxygen *isotope* $_8O^{16}$.
The atomic nucleus is charged positively, and each of the electrons rotating about it carries a negative electric charge, which is never less than a definite value called the *elementary electric charge.* The positive charge of the atomic nucleus is precisely equal to the sum of the negative charges of the electrons contained in the shell of the atom. Therefore an atom is electrically neutral in its normal state. The number of positive charges of a nucleus is what determines the atomic, or ordinal number of a given element in Mendeleyev's Periodic Table of Elements. Under the effect of external causes a nucleus may lose or capture electrons and become either a positive ion, if electrons have been lost, or a negative ion, if it has temporarily captured an extra electron from a neighbouring atom or from among the free electrons present in its environment.
Electrons are held in their orbits by the forces of electrical attraction acting between them and the nucleus and form a unified harmonious system. Each electron possesses a definite store of energy depending on the distance at which it rotates about the nucleus. The farther the electron is from the nucleus, the higher is its energy, although with an increase in this distance its bond with the nucleus naturally weakens. However, no two electrons can be in the same energy state (in the same orbit) and therefore electrons are arranged in layers (levels) in the shell. There may be only a strictly limited number of electrons in each level:

2 in the first, innermost layer, 8 in the second level, 16 in the third, 32 in the fourth, and so on. Following the second level the electron orbits are divided into sublevels.
The chemical properties of an atom, i.e., its ability to enter into chemical reactions, are determined, as a rule, by the electrons of the outermost levels, because, being the least bound with their nucleus, they react with other atoms more readily.



In all chemical transformations of substances in nature certain complex substances are always converted into simpler ones, and vice versa. These processes are always accompanied by the expenditure or liberation of energy.
Atomic and nuclear models. All our knowledge of the atom and its nucleus is based on very indirect methods of research. Therefore the terms "the structure" of the atomic nucleus, its "representation", and other similar expressions are nearly always conventional. Firstly, the atomic nucleus is invisible, and secondly almost every new, not only fundamental, but particular discovery in nuclear physics often makes scientists modify, improve and sometimes even chan-

ge completely the picture of the structure of this most important building block in the microworld.
Therefore, to avoid creating the wrong, unscientific picture of the phenomena described, physicists usually speak of an atomic, or nuclear model. This term reflects more correctly and accurately the state of the latest factual knowledge and conceptions of the mysterious world the study of which has become the paramount objective of many generations of scientists.
The first atomic model dates back to the end of the 19th century. It was J. J. Thomson's "raisin pudding model". This prominent scientist believed that the indivisible atom of, say, carbon represents a sphere—a solid cluster of positively charged electricity with six electrons embedded in it. The total negative charge of these electrons is precisely equal to the positive charge of the entire sphere, and this explains why the atom is always neutral in the normal state, and only the loss of one or more electrons by it leads to the formation of a positively charged atom, i.e., a positive ion.
The discovery of radioactivity and the atomic nucleus forced the scientists to revise the atomic model. This was done by E. Rutherford, who advanced a new, so-called *planetary model* of the atom patterned after the solar system.
According to this model the atom consists of a positive nucleus located in the centre of the atom, while the electrons rotating about the nucleus form a cloud of orbits. It is on the number of these rotating electrons that all the chemical properties of the elements depend.
This model marvellously represented the structure of the

hydrogen atom. Its nucleus was a positively charged particle—the proton, with a single electron rotating around it. The charges, masses and sizes of the two particles were the same.

The nuclei of all the other elements are heavier than the proton. For instance, the mass of the nucleus of the element following hydrogen in the Periodic Table, helium, with two electrons rotating about it, is four times the mass of the proton, and so on. And finally, the atomic nucleus of uranium with 92 electrons in its orbits is 238 times as heavy as the proton.

At first this complicated representation of the mass of the atomic nucleus caused no particular inconvenience, since at the time it was considered more important that the number of electrons, and hence of the negative electric charges in the atom, precisely coincided with the total positive charge of the nucleus (which also corresponded to the atomic number of the element), and therefore a "normal" atom was always neutral. All this was ideally confirmed by the Mendeleyev Table, where some of the elements were arranged, not in the order of increasing atomic weights, but in accordance with the number of electric charges, i.e., electrons in the atomic shell.

Ever since the scientists first succeeded in determining the atomic weights of various elements they were always amazed at the regularity with which this weight increased from element to element in multiples of the weight of the lightest element—hydrogen.

As early as 1815 a London physician and ardent enthusiast of chemistry, William Prout, posed the question: if the atoms of all chemical elements were the primary

basic particles, virtual "bricks" of the Universe which could not be decomposed and were not at all bound with each other, what could explain the fact that the nitrogen atom weighs exactly 14 times and the oxygen atom exactly 16 times as much as the hydrogen atom?
This brought the inquisitive investigator to a very far-sighted conclusion that all chemical atoms are made up of multiples of hydrogen atoms, somehow bound together. The nitrogen atom is composed of 14 hydrogen atoms, the oxygen atom of 16 atoms of hydrogen, and so on.
If this brilliant conjecture had been accepted by the scientists of that time, it would have greatly speeded up the further development of physical science. But ... subsequent, more accurate measurements of atomic weights showed that some elements have fractional atomic weights based upon the atomic weight of hydrogen as unity. Besides, the deviations are sometimes so great that they cannot be attributed to errors of measurement. At the time nobody could convincingly deny or explain these divergencies between the tempting hypothesis and scientific facts, and this extremely intriguing idea of the inquisitive physician sank into oblivion and was again revived, in a new version, only in the 20th century.
As has been clearly demonstrated by many centuries of research, all great facts of nature turned out to be the simplest in the final analysis. Rutherford proved that the nuclei of all atoms are positively charged. And the proton is unquestionably the nucleus of the hydrogen atom. But if one considers that the nuclei of all other atoms consist of a set of protons, then one point remains a puzzle. The charge of the nucleus and the atomic weight coincide numerically

only for hydrogen. For all other elements they diverge quite substantially, by a factor of 2 to 2.5. But the number of protons in a nucleus cannot exceed the total nuclear charge. Isn't there something funny about protons changing their mass from one element to another? Or maybe the atomic nucleus contains some other, yet unknown particles?

As the science of the atomic nucleus developed further, the need to clear up this contradiction once and for all became more and more urgent. Then a new nuclear model was proposed which seemed to obviate this difficulty.

It was still believed that the nuclei of all atoms are made up of protons whose number is precisely equal to the number of electrons, i.e., to the atomic number of the element. However, in addition to them the nucleus contains protons closely bound with electrons, which neutralize their positive charge.

It is the number of such neutralized protons that constitutes the difference between the atomic weight and the sum of the positive nuclear charges.

This model offered a plausible explanation of the facts known at that time. As to the presence of electrons in the nucleus, it was proved by the disintegration of the nuclei of radioactive elements in the course of which very genuine electrons were ejected by them.

Very soon, however, many new contradictions arose. For instance, the repeatedly verified fact that the mass of the proton and the electron allegedly bound with it, when multiplied by the above-mentioned difference between the atomic number of the element and the mass of the nucleus, was still considerably less than expected. The "arithmetic"

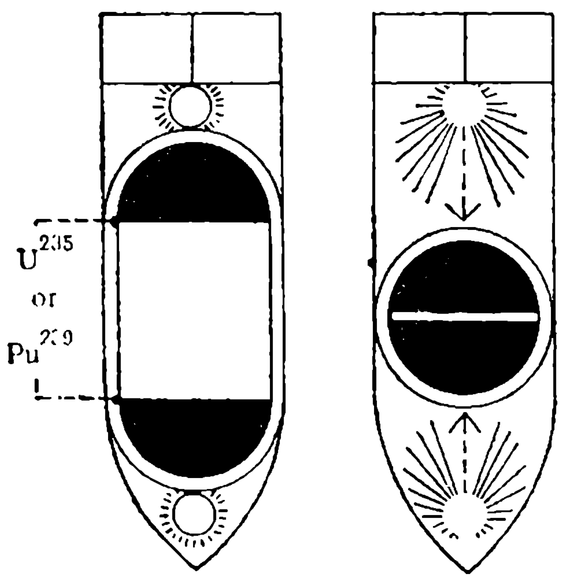
did not work. Therefore this model was soon discarded. The discovery of the neutron in 1932 (see *Neutron*) immediately cleared up the confusion and greatly simplified (in fact complicated) the picture of the internal structure of the atom. Soon after this discovery was published D. Ivanenko, a Soviet scientist, proposed a new, strikingly pictorial model of the structure of the atomic nucleus. His theory stated that the nuclei of all atoms, as had been thought before, consist of protons, whose number is equal to the sum of their positive charges, i.e., to the atomic number of the element in the Periodic Table. In place of protons coupled with electrons the nucleus contains neutrons--new particles whose mass is equal to that of the protons but which carry no electric charge, that is, are neutral. Their number exactly accounts for the difference between the mass of the whole atomic nucleus and the number of protons in it and the "arithmetic" works ideally now.

According to this model the nucleus of helium consists of two protons and two neutrons. The sum of the positive charges of the nucleus and the number of electrons in the shell are equal to the number of protons (2), the mass of all the protons and neutrons being equal to the atomic weight of the element (4). Similarly, the nucleus of lithium contains 3 protons (a quantity equal to the atomic number of the element and to the number of electrons in their orbits), while the sum of the protons and neutrons equals 6, which corresponds to the atomic weight of the element.

And so throughout the Periodic Table.

The discovery of the neutron also perfectly explains the existence of *isotopes*—varieties of atoms of the same element

which slightly differ in mass; this difference is caused by the different number of neutrons in their nuclei.
The new model of the atomic nucleus was immediately accepted by the scientists. It fully agrees with the numerous facts accumulated so far, indicates new ways for refining the picture of the nuclear structure, and gives a new impetus to the further development of theoretical research.



Atomic (nuclear) bomb. One of the weapons of explosive action with a warhead of tremendous destructive force, in which a *self-sustaining chain reaction of nuclear fission* of uranium-235 or plutonium-239 is used.
The basic elements of this bomb are a charge of nuclear fuel, an explosive device, and a shell. Before the explosion, the charge of the fissionable material with a total mass exceeding the critical size (see *Critical mass*) is divided into two or more parts, the mass of each being below cri-

tical. The explosive device is designed so as to join together the two halves or all the parts of the divided overall charge as quickly as possible. for instance "shoot" them against each other. A branching fission chain reaction starts instantaneously in the mass of fissionable material which becomes above-critical since that moment. The reaction terminates in an explosion after several millionths of a second.

An atomic bomb explosion is accompanied by a powerful explosion wave, light radiation and penetrating radiation, which are followed by radioactive contamination of the surrounding area, air and water.

The force of an atomic bomb is usually evaluated in terms of the TNT equivalent, i.e., the amount of a conventional explosive (trotyl, TNT) which would be needed to achieve the same effect powerwise as was achieved by the explosion of this atomic bomb (1 g TNT is equivalent to 1 kcal, see the picture on p. 40).

Atomic defence. A system of measures aimed at protecting people, animals, and property from an atomic attack by the enemy, and also measures for rendering timely medical aid to casualties, decontamination of the area and structures, rapid elimination of the damage caused by the attack. Included here are also the setting up of shelters, training of the population, forming anti-aircraft and atomic defence detachments, and carrying out preventive, fire-protection and other measures.

Atomic weight (atomic mass unit—amu, or mass unit). The weight of an atom is so small that it would be extremely inconvenient to designate it, say in grams, each time. We would have figures with tens of zeros. Therefore it is

usually expressed not in grams, but in arbitrary units in which the weight of an oxygen atom is taken to be 16. The ratio of the weight of any atom to the weight of 1/16 fraction of the oxygen atom ($_8O^{16}$) is what we call the *atomic weight*. In this case the atomic weight of the lightest chemical element—hydrogen—should be equal precisely to unity. However, since oxygen atoms have several isotopes the ratio cannot be expressed by an integral number, and the atomic weight of hydrogen is actually equal to 1.008.
The weight of 1/16 fraction of the oxygen atom is 1.67×10^{-24} g. This is called the *atomic mass unit*.
In 1961 the scientists agreed that the atomic mass unit should be equal to the ratio of the weight of an atom to the weight of 1/12 fraction of the atom of the principal isotope of carbon, $_6C^{12}$.

B

Beta decay. If we consider the transformations of atomic nuclei of some radioactive elements into others (see *Radioactivity* and *Radioactive series*), we can see that most of them are accompanied by the emission of either electrons (beta-particles) or alpha-particles. The emission of alpha-particles seems more or less understandable. These are fragments "detached" from a disintegrating atomic nucleus. But how do electrons get into the nucleus? We know that it consists only of protons and neutrons.
The only possible answer would be that these electrons

are produced in the nucleus as a result of certain intranuclear transformations. This was actually established in relation to the disintegration of the atomic nucleus of tritium (superheavy hydrogen) consisting of one proton and two neutrons. A nucleus of the isotope helium-3 consisting of two protons and one neutron, and a free electron are produced instead. One neutron has disappeared somewhere, but a proton and an electron have appeared in its place. Thus, the production and emission of an electron was achieved at the expense of the transformation of one of the neutrons into a proton.

Other nuclear reactions are also known where, instead of an electron, the atomic nucleus emits a positron—the precise counterpart of the electron, but with a positive electric charge. For instance, the radioactive isotope nitrogen-13 consisting of seven protons and six neutrons transforms after disintegration into a nucleus of carbon-13, which has six protons and seven neutrons, and emits one positron in the process.

The natural bewilderment of the scientists was dispelled when it was established that in the course of radioactive disintegration of excited atomic nuclei protons and neutrons can transform into each other and an excess positive or negative charge is carried away either by the electron or by the positron. In the case of electron radioactivity, when one of the neutrons turns into a proton and the negative charge is carried away by the electron, the total positive charge of the nucleus increases by unity. And now it will be the nucleus of the isotope of a new, heavier element from the Periodic Table, for instance, helium-3 instead of tritium-3. In positron radioactivity, where a proton turns

into a neutron and the positive electric charge is carried away by the positron, the total positive charge of the nucleus decreases by unity, as a result of which there appears a nucleus of an isotope of a new, lighter element, for instance, carbon-13 instead of nitrogen-13.

After everything had been neatly arranged in "pigeon-holes", a new puzzle arose—a lack of energy balance. In beta decay the nucleus loses a certain amount of energy, and since an electron or positron emitted by it may have very different energies, part of the energy is lost altogether. Some scientists proceeding from idealistic standpoints were overjoyed and announced the violation of the law of conservation of energy. But their joy was short-lived. Soon afterwards it was proved that simultaneously with an electron or positron the nucleus emits one more particle having no electric charge and possessing a negligible mass, but flying with a colossal velocity, close to that of light. The new particle was named the *neutrino*—a tiny neutron. This is the particle that carries away the small portion of energy missing in the precise balance.

Thus, the transformation of a neutron into a proton inside the nucleus is accompanied by the emission of an electron and a neutrino, while the transformation of a proton into a neutron is attained by the emission of a positron and a neutrino.

Beta-particles. One of the types of radiation emitted by the nuclei of radioactive substances during disintegration. Beta-particles are ordinary electrons (see *Electron—"the atom of electricity"*).

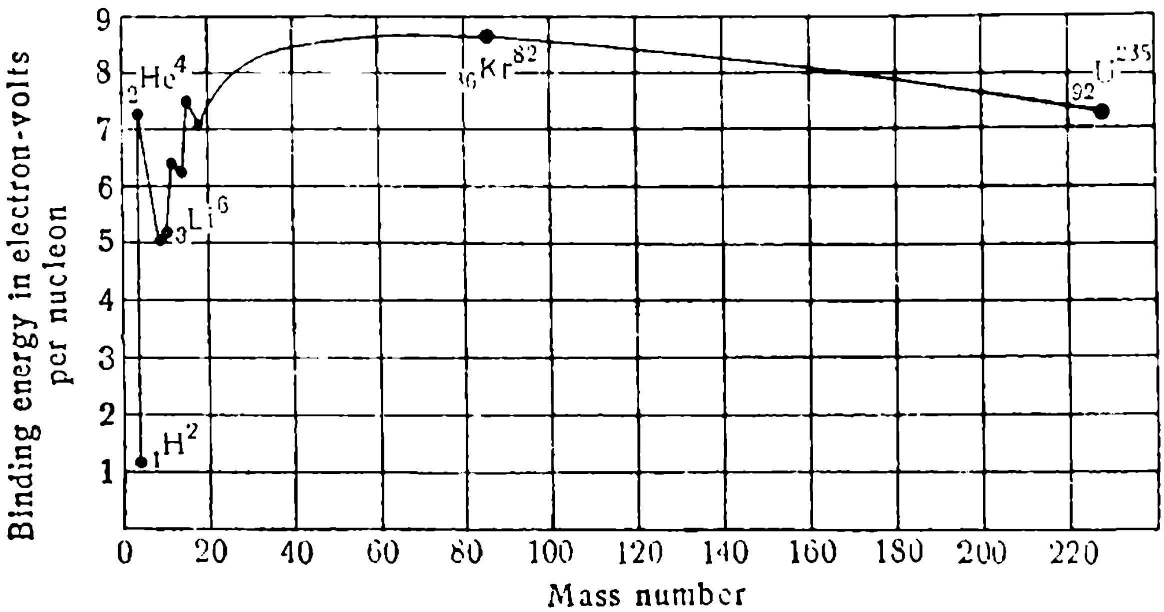
Betatron. A circular accelerator. The machine consists of an annular vacuum chamber in the shape of a doughnut; it

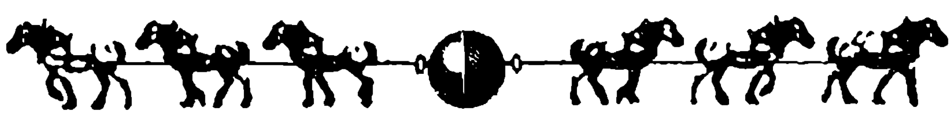
is placed between the poles of an electromagnet which sets up a changing magnetic field. An electron source is placed inside the chamber (see *Electron gun*).
Electrons move in the betatron along a circular path. As the magnetic field penetrating the chamber changes, an eddy electric field arises, which entrains the electron flux. At the same time the magnetic field sets up a force directed perpendicularly to the motion of the electrons. This is the force that retains the electrons in the circular path. Betatrons make it possible to accelerate an electron flux to energies from several million electron-volts (eV) to 100-200 MeV. Small betatrons of several million electron-volts are widely used in technology and medicine.

Binding energy (of the neutron, proton, electron, etc.). The energy necessary for the complete separation of a given particle from the nucleus.

Binding energy of the atomic nucleus. In order to estimate the amount of energy which could be released in rearranging the elementary particles in atomic nuclei scientists have compiled a table of average energies (in electron-volts) stored up by each nucleon in atomic nuclei. The table makes it possible to establish in what cases this energy could or could not be liberated, i.e., to calculate the difference between the bound-state energy of a certain set of nuclear particles and the energy of a state where these particles are separated and removed from each other.
It can be seen from the graph that the highest value of the average binding energy, which is equal to about 8.6 MeV per nucleon, refers to atomic nuclei of chemical elements occupying almost the entire middle part of Mendeleyev's

Table. No matter how we rearrange the nuclei of these atoms the energy spent on this work will be equal to the energy released with any other arrangement of the particles, or will even exceed it; consequently we shall gain nothing by these operations.





However, the elements located at the very beginning and the very end of the Table, i.e., the lightest and the heaviest elements, are characterized by considerable fluctuations in the average value of binding energy.
For instance, the total binding energy of the atomic nucleus of helium, which consists of four nucleons, is 28.2 MeV, i.e., 7 MeV per nucleon, while the total binding energy of the nucleus of deuterium, which contains two nucleons, is 2.28 MeV. And if we could combine two nuclei of deuterium

into a nucleus of helium, the actual energy gain on each such atom would be 23.6 MeV!
A kilogram of helium contains 1.505×10^{26} atoms. If we produce a kilogram of helium using deuterium nuclei, the energy released should be equal to $1.505 \times 10^{26} \times 23.64 = 35.6 \times 10^{26}$ MeV. To obtain this amount of energy in the usual way it is necessary to burn 13,600 tons of gasoline!
Another example. The total binding energy of the atomic nucleus of uranium-235, which consists of 235 nucleons, is 1,786 MeV (7.6 MeV per nucleon). The binding energy of the two fission fragments, which are nuclei of lighter elements from the middle of the Periodic Table, is much higher (8.6 MeV per nucleon); if we add the energy of the ejected 2 or 3 neutrons, it will equal about 2,000 MeV. And so, the difference in energy between the atomic nucleus of uranium and its two fragments will come to about 200 MeV. The fission of all nuclei of one kilogram of uranium-235 will release an energy which can be obtained only by burning 1,800 tons of gasoline or 2,500 to 3,000 tons of coal.
Thus, a reaction of fusion of light-element nuclei liberates about 8 times as much energy as a reaction of fission of heavy-element nuclei.

Biological effect of radioactive radiations. Like any other substances, the atoms and molecules of living cells ionize under the effect of X-rays, gamma-rays, and a flux of charged particles with resulting physicochemical changes affecting the nature of their subsequent vital activity, in particular the hereditary features of the organism.
According to some scientists, the ionization of atoms and

molecules under irradiation leads to the rupture of chemical bonds in complex protein molecules, which are extremely sensitive to any external effects. According to other theories, the primary reactions take place in the water of which the body tissues are mainly composed. The water then decomposes into hydrogen and a free OH radical, which combine with the protein molecules, causing changes in their chemical structure. Changes in the normal chemical processes in the tissues disturb the metabolism, and this often results in the reverse development (degeneration) of the organism cells.

Many Soviet scientists believe that all changes in living cells are determined by the reflex mechanism, since it is the nervous system that reacts to ionizing radiations in the first place. As to the changes in the tissues and organs, they should be considered merely as secondary phenomena. Intensive action of radiations on a living organism may cause so-called *radiation sickness*.

Biological shielding. A system of shields or protective walls aimed at reducing the intensity of radioactive radiations to a level safe for the human body The shields are placed between the radiation source and the zone where people may be present.

The selection of the material for the shield depends on the type, intensity and penetrating power of the radiation and also on the design and cost of the unit. The shields may consist of one or several layers. The sequence of the layers is of great importance. Thus, gamma-ray protection requires materials containing elements of high mass number. This is usually a shield in the form of a concrete wall or shell many metres thick. For protection from alpha- and

beta-particles use is made of thin single-layer shields constructed of light metals or plastics.
Neutron shielding is the most complicated. Having absorbed a neutron, atoms of most substances become excited and then disintegrate, emitting other particles and penetrating gamma-quanta. Therefore neutron shields have to be made up of two layers, the first consisting of light elements (water, graphite, etc.), which efficiently moderate neutrons, and the second of heavy elements (iron, lead, and especially concrete), which weaken secondary gamma-quanta resulting from the capture of the moderated neutrons by the first layer. Of great importance are technical and economic considerations. In stationary reactors, where the weight and size of shielding are not rigidly restricted, one may use the cheapest materials—ordinary water, concrete, etc. In power reactors for transport purposes, for instance, for marine vessels, where the reduction of the weight and size of biological shielding is of decisive importance, it is necessary to use more efficient and costly materials—lead, boron carbide, boral, hydrides of certain metals, special steel. Apart from the reactor itself. biological shielding is set up around the whole heat-removal system, including piping, pumps, and the heat exchanger and also all arrangements and rooms in which spent rods are withdrawn automatically, transported, stored, and so on.
Shielding is also used to protect the channels through which the materials to be irradiated are introduced into the reactor, the channels for extracting neutron beams of various energies from the core, and other devices.
When the heat-transfer agent is simultaneously used as the working substance serving to actuate steam turbines

(for instance, in a boiling reactor), biological shielding has to be built around the turbine and all steam pipes where the superheated and spent steam circulates (including coolers).

Bremsstrahlung* (braking radiation). If a particle flying with a high velocity absorbs a certain amount of energy from an external source, its velocity will be changed immediately—it will increase by a strictly definite amount corresponding to this energy. And conversely, in the case of abrupt deceleration—"braking"—the liberated energy will be emitted in the form of X-rays. This radiation is called *bremsstrahlung (braking radiation)*.

For instance, when a flux of electrons accelerated to energies exceeding 12 keV suddenly slows down (in colliding with atoms of the high-melting tungsten anode of an X-ray tube), X-rays of various wavelength are produced.

Bubble chamber. In spite of the fact that many years have elapsed since the *Wilson cloud chamber* was invented and many improvements have been introduced into its design, it still remains an amazingly simple apparatus which nevertheless gives accurate and extremely convincing results. But the physics of the atomic nucleus more and more frequently has to deal with exceedingly fast particles contained in cosmic radiation or produced with the aid of modern superpowerful accelerators. These particles, on passing through a cloud chamber, often leave behind such a short, weak and broken track, which even has no time to deviate from a straight path, that it cannot be measured with sufficient

* From the German words *bremsen*, to brake, and *strahlung*, radiation.—*Ed.*

accuracy. As a result, all the most important and interesting phenomena escape observation. Besides, at the moment when the gas in the cloud chamber expands, currents and eddies arise which displace and distort the particle track, although not very considerably. It is often necessary to know precisely the sequence of appearance of these tracks—which of them is the first, which the second, and so on, up to the last one, which of them passed higher, and which lower.

The cloud chamber does not answer these questions.

How could it be made to supply this information? Boiled water came to the rescue. What is the first sign of boiling? The appearance of bubbles. But how and where do they originate? Hardly anybody paid special attention to this. The formation of bubbles has proved to be of great and even decisive importance in the physics of boiling of liquids. Experiments have shown that vapour bubbles originate mainly on the walls of the vessel in which the liquid is being heated, at spots where there are tiny depressions or projections which practically cannot be eliminated by any, even most thorough grinding or polishing. Such irregularities serve as the centres of formation and further growth of bubbles.

If a liquid contains suspended particles of a solid or if some gas is dissolved in it, such solid and gas particles may become the centres of formation of vapour bubbles.

If, however, very pure water is heated in a vessel with ideally polished walls, so that any, even the slightest shocks and vibrations are avoided, the water can be superheated, i.e., raised above its normal boiling point. If, however, the vessel is pushed even slightly, or if the state of quies-

cence of such superheated water is disturbed in any other way, then boiling is immediate.

This phenomenon gave physicists the idea to use a superheated liquid in the cloud chamber in place of a cloud of an invisible vapour.

When a charged particle passes through a superheated liquid and ionizes its molecules, these molecules will become the centres of formation of vapour bubbles along the entire path of the particle, i.e., this ionizing particle will leave in its wake a trail of bubbles that can be illuminated and photographed.

Still another method can be used. It is well known that a liquid can be superheated if it is subjected to a superincumbent pressure above atmospheric pressure. If this pressure is quickly reduced to atmospheric, the liquid does not boil immediately, but remains quiescent for a time. During this period of quiescence, a passing ionizing particle leaves behind it a trail of bubbles which can be photographed.

What are then the advantages of the superheated-liquid chamber over the ordinary "mist" chamber? There are many.

Any liquid is much denser than water vapour, and therefore it slows down the particles passing through it more efficiently. Due to this the ionized tracks of the particle remain more dense and continuous, and lend themselves more readily to observation and measurement. Bubble formation proceeds much faster in a superheated liquid than in a vapour, and besides the motion of the particles of the liquid itself is less perceptible than the motion of light vapour particles, and therefore the trail of bubbles left be-

hind by a particle in the liquid is distorted much less than in the "mist". And finally, what is very important and is the main advantage of such a chamber, vapour bubbles, once formed around the ionized liquid particles, will grow continuously and become large enough to be photographed. By taking a number of photographs it is possible to establish accurately enough from the size of the bubbles, which of the tracks appeared earlier and which later.

A "superheated" liquid does not always mean a liquid heated to a high temperature. There are quite a number of liquids "boiling" and turning into a vapour not only at room temperature, but also at a considerably lower temperature or at a slight decrease in the external pressure (liquid hydrogen, propane, isopentane, etc.).

The gas filling the bubble chamber, which is liquefied and consequently highly pressurized, is also ideally transparent. But if the pressure is reduced to a critical value at which the liquid does not boil immediately because there are no centres in it promoting the formation of bubbles (dust particles, charged particles, and so on), then as soon as a charged particle passes through such a superheated liquid, which is ready to boil at any moment, its ionized track, densely covered with gas bubbles, becomes visible. Such a chamber does not contain any pistons or other movable parts, and its size may reach several metres in length. This is just what the scientists need!

And some more. If the cloud chamber enables us to observe tracks left behind by charged particles penetrating it only for fractions of a second, the bubble chamber makes it possible to observe particle tracks for much longer periods. This is a great, sometimes even a decisive advantage.

The importance of the new chamber becomes especially evident if we recall that by using powerful particle accelerators scientists can now impart to these particles such velocities and energies which are not encountered in natural or artificial radioactive substances and will probably become commensurate with the velocity and energy of cosmic particles.

It is due to the use of bubble chambers and other units similar to them in design and operation that most of the discoveries in contemporary physics are made.

C

Capture of neutrons by atomic nuclei. When a free neutron approaches an atomic nucleus of another substance within the range of action of powerful nuclear forces (10^{-13} cm), then, depending on its velocity (energy), it may either fly past the nucleus of this atom or be drawn into it. Addition of a new, extra neutron brings the nucleus of such an atom to an excited state and results in the formation of a so-called intermediate nucleus, which disintegrates after a short period of time, liberating a certain amount of energy by emitting a proton, neutron, alpha-particle or gamma quantum.

Cerenkov-Vavilov counter. Cerenkov-Vavilov radiation lies at the basis of a whole range of counters of fast particles: electrons, protons, mesons, and high-energy gamma-quanta. They trap, greatly amplify and record either all the light

emitted by the particle, or the light emitted only at a strictly definite angle to the direction of the particle motion. By passing particles under study successively through a row of such counters it is easy to establish their precise velocity, and, by combining them with other counters and devices, it is possible to determine their mass, charge, and other characteristics. In 1958 the Soviet scientists P. Cerenkov, I. Frank and I. Tamm were awarded the Nobel Prize in physics for this important discovery and the development of the radiation theory. Unfortunately, S. Vavilov did not live to witness this solemn occasion.

Cerenkov-Vavilov effect. A glow appearing in a certain transparent substance when a charged particle flies through with a velocity exceeding the phase velocity of light in the same substance. This glow effect was discovered by the Soviet physicists P. Cerenkov and S. Vavilov.

This kind of radiation proved to be truly remarkable. It propagates not in all directions, but in the shape of a cone whose axis coincides with the direction of the particle motion. The value of the angle at the cone apex strictly depends on the velocity of the particle and the refractive index of the substance for a definite wavelength of radiated light. Therefore it became possible to apply this phenomenon in devices for highly accurate measurements of the velocity and direction of flight of fast charged particles—electrons, protons, mesons, since the brightness of radiation increases with velocity of the particle which causes it and is directly proportional to the square of its electric charge.

Chain reaction. One of the most remarkable scientific achievements of the 20th century is the discovery of chain reactions—at first of chemical ones (in 1913) and then, three

decades later, of nuclear chain reactions. By these are meant chemical reactions which, once started, proceed of their own accord until the reactants are completely spent. Such reactions may be *self-sustaining* at some initial level or *branching* according to a certain, for instance, geometric progression.
An example of the first, non-branching type of chemical reaction is the addition reaction between hydrogen and chlorine. These elements are so strongly attracted to each other that a hydrogen atom easily tears one of the two atoms of the chlorine molecule away from it and adds it on, or, vice versa, a chlorine molecule tears away one of the two atoms of the hydrogen molecule and adds it on. The chlorine atom which remains free immediately compensates for the loss by detaching one of the two atoms of another neighbouring hydrogen molecule, and so on. This continues until all the chlorine atoms have added on one molecule of hydrogen each or, vice versa, until each hydrogen atom has added on a chlorine molecule.

An example of a branching reaction is the addition reaction between hydrogen and oxygen where a hydrogen atom tears away and adds on one of the atoms of the oxygen molecule. A so-called free OH radical is then formed. The second oxygen atom which remains free immediately tears away and adds on one of the two atoms of the hydrogen molecule, and thus one more free OH radical and one free hydrogen atom are formed.
As a result of this process two free hydrogen atoms remain, each of which starts its own chain of tearing away and adding oxygen atoms. This second "generation" leaves behind already four free hydrogen atoms; these, in their

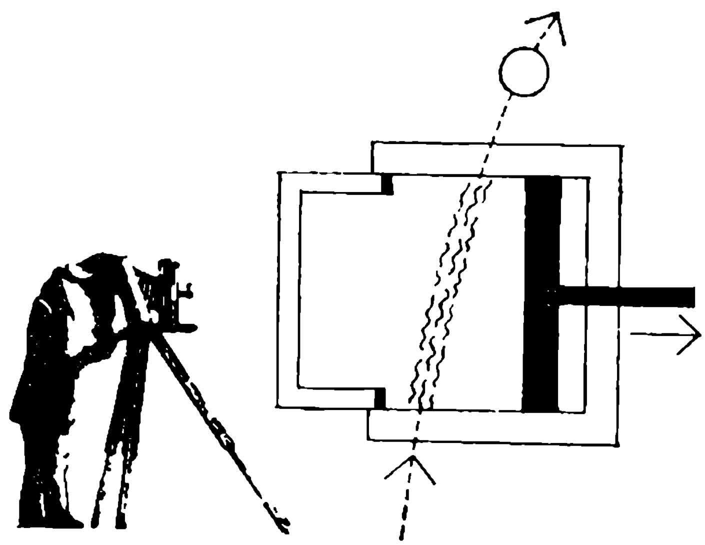
turn, leave eight, the next generation 16, and so on, i.e., the number of free atoms ready to start their own multiplication chain doubles with each generation, increasing unrestrainedly like a snow avalanche. All this terminates in the complete exhaustion of the initial gases or in a powerful explosion. In short, each unit entering into the reaction causes a reaction in K other units. Then each of these K units causes a reaction in another K units, i.e., K^2 units will now be involved in the reaction, and so forth. The number K in this case is called the *multiplication factor*. If this factor is, for some reason, below unity, the reaction will gradually begin to die out; if it is above unity, the reaction will begin to increase. When the value of K is precisely equal to unity, the reaction rate remains at the same pre-assigned or initial level.

Cloud chamber (Wilson cloud chamber, expansion chamber). The advances in the design of charged-particle counters posed the following question before the scientists: would it be possible to try and "see", in some way or other, the particles making up the atom, although they are thousands of millions of times smaller than the smallest bodies which can be seen under the most powerful optical microscopes?

Usually, when visibility is poor or obstructed we say "everything is in a mist". In certain cases, however, at least in the field of physics, a "mist" enables us to turn the invisible into the visible. This somewhat surprising circumstance is associated with the question: why and how do clouds form in a clear sky and why does it rain?

The air, no matter how dry and clear, always contains a certain amount of moisture, which is continuously evaporated from seas, lakes, rivers, plants, and the soil. These

water vapours are invisible, since the individual vapour molecules are uniformly distributed in the air and do not change its homogeneity, just as salt molecules dissolved in water are invisible.
But if the atmospheric pressure reduces for some reason, then the vapour contained in the air becomes oversaturated. As a result, individual moisture molecules join, at first



into droplets visible in the form of the familiar "vapour" and clouds, and later into larger drops, which, being unable to float freely in the air, precipitate as rain.
Moisture, however, can collect into drops only when the air contains a sufficient number of small dust particles, especially if they carry electric charges. They are what we call *centres of condensation of moisture.*
Otherwise vapour molecules cannot join into drops even in the presence of a great excess of moisture in the atmosphere.
In 1912 the English physicist Charles Wilson, who had previously done much work on the origin of rains and mists,

suggested an extremely ingenious and amazingly simple way to "see" charged particles. To do this, it was only necessary to create something like an artificial mist in a chamber filled with a supersaturated vapour. Charged particles flying through the chamber ionize the vapour molecules, and the ions formed serve as centres of condensation of the water vapour. The liquid droplets form visible chains (tracks).

The chamber consists of a glass cylinder with a movable piston forming its bottom. The cylinder is filled with vapours of an evaporating liquid, for instance, alcohol. If we lower the piston very quickly, the pressure and consequently the temperature of the vapour in the chamber will drop abruptly with the formation of an excess of moisture, i.e., the vapour will be supercooled and supersaturated. Since the vapour entering the chamber is carefully cleaned of dust and other suspended particles, the moisture molecules have no centres on which to collect and no mist will appear inside the chamber.

If, however, a charged particle, even a very fast one, passes through the chamber at this critical moment, it will as usual continuously break vapour molecules down into ions on its path, i. e., it will produce charged particles, which will immediately become centres of vapour condensation. The particle track will instantaneously be covered with a great many moisture droplets, eagerly precipitating on the ions, and more or less distinct thin lines of "tracks" will become visible, the disintegration of which into separate drops can be observed only under a powerful microscope. These tracks become especially clearly observable if they are strongly illuminated from the side, and if the chamber interior and

the piston are coated with a dull black paint. If we synchronize the lowering of the piston with the shutter of a camera and a light flash, the tracks of the passing particles can be easily photographed.

The cloud chamber not only provides visual evidence of the tracks of individual particles, but also makes it possible to determine certain qualitative characteristics of these particles. For instance, the thickness and purity of the track indicate whether the charged particle travels slowly or rapidly: the slower it flies, the larger is the number of gas molecules ionized on each centimetre of its path. By measuring the width or density of the track it is possible to determine rather accurately the velocity of the unknown particles under investigation. By the number of droplets in the track, if the latter terminates within the chamber, it is possible to determine the total number of ion pairs produced by the charged particle which has just passed. And knowing the energy needed for the formation of an ion pair one can compute the total energy which the particle had at the moment it appeared in the chamber.

Later, the cloud chamber was considerably improved. An especially valuable contribution to its design was made by the Soviet physicists P. Kapitza and D. Skobeltsyn who suggested in 1927 that the chamber be placed in a strong magnetic field. Interacting with charged particles, the magnetic field forces them to deviate from a straight path, and this makes it possible, in the first place, to determine whether the particle is charged positively or negatively, and secondly to determine the energy of the particle by still another method, because the faster it moves or the larger its mass, the less its path deflects in the magnetic

field. And finally, what is most important, it is possible to investigate all the phenomena observed on collision of these particles with the atoms of the vapour filling the chamber, or with the atoms of target materials interposed in the path of the particles. In such cases one can even study the behaviour of particles carrying no electric charge—by the tracks of charged particles scattering as a result of such collisions.

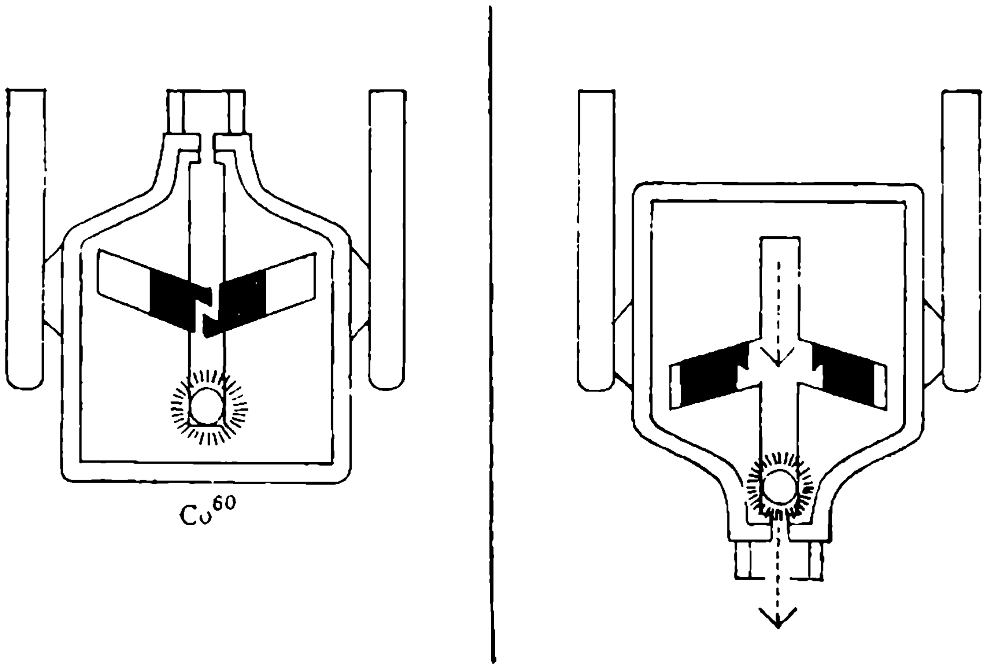
Cobalt, Co. A high-melting metal which finds wide application in metallurgy in the production of temperature-resistant and magnetic steels and alloys, and also in other branches of industry. It is one of the few chemical elements having only one natural isotope, whose nucleus consists of 27 protons and 32 neutrons ($_{27}Co^{59}$).

If cobalt is irradiated with an intensive neutron flux in a nuclear reactor, it turns into an artificial radioactive isotope cobalt-60 ($_{27}Co^{60}$) with a half-life of 5.25 years which emits gamma-rays of 1.33 and 1.17 MeV energy and relatively weak beta particles of 0.31 eV energy.

Cobalt-60 is used in technology for flaw detection in huge metal ingots and finished products, in chemistry for irradiating and producing synthetic plastics with new properties, in medicine for treating the worst disease of humanity—cancer, for sterilization of drugs and medical apparatus, in agriculture for preventing the germination of potatoes, for pest control, the stimulation of plant growth, and so on.

Cobalt bomb (cobalt irradiation unit). In order to stop gamma-rays emitted by radioactive cobalt-60 (of 1.33 MeV energy), to provide safety and the opportunity of using the radiation for scientific, medical and technological pur-

poses, this element has to be stored in thick-walled lead or steel containers. Such a container, equipped with instruments, controls and devices permitting the escape of a narrow beam of gamma-rays, is called the *cobalt bomb* (see the picture).



Colliding beams (of accelerated particles). A new trend in the development of accelerators for particles of super-high energy, of the order of 10^{10} and 10^{11} electron-volts. It is based on the fact that in a head-on collision of two accelerated beams of particles of, say, 130 MeV energy each it is possible to obtain particles with an interaction energy of 70 GeV due to the conversion of part of the mass of the accelerated particle into energy; with conventional methods this would require gigantic proton synchrotrons 50 m or more in diameter. The workers of the Novosibirsk Institute of Nuclear Physics have designed a unit in which a collision of an electron and a positron beam of 700 MeV each

produces new particles of an energy of two million millions of electron-volts!

Controlled chain reaction of nuclear fission. Let us imagine that a single neutron penetrates into a piece of the fissionable isotope uranium-235. Hitting one of the atomic nuclei of uranium-235, it will split it in two. A relatively great amount of energy will be liberated (about 200 MeV), but the most important thing is that as a result of the fission of the nucleus of uranium-235, two free neutrons will be ejected which will split the two nuclei, forming four neutrons. These four neutrons will split another four nuclei of uranium-235. The four nuclei will now eject 8 neutrons capable of splitting the same number of uranium nuclei. The nuclear fission and liberation of neutrons will then proceed avalanche-like, the number of neutrons being doubled in each new generation. In short, a self-sustaining chain reaction of nuclear fission will begin.

In order to determine straightway how rapidly the rate of this reaction will increase in a given piece of fissionable material, a special quantity called *multiplication factor*, K, is introduced.

This factor indicates by how many times each successive generation of neutrons produced exceeds the preceding one, that is, by how many times the neutron flux increases after the utilization of each next portion of newly born neutrons.

If this quantity exceeds unity even by one thousandth of one per cent, the number of neutrons, as well as the number of fissions of the nuclei of uranium-235 will build up in avalanche-like fashion all the same. But in order to utilize nuclear energy for the benefit of mankind, it should be

made controllable; in a controlled reaction the number of fissions per unit time, and hence the amount of energy, is increased gradually and after the required level is achieved, it should be kept constant. This is evidently possible only if by a certain moment the multiplication factor becomes equal to unity. If it drops below unity, the reaction, which has already started, will die out.

How could then a controlled nuclear chain reaction be achieved?

A chain reaction generally cannot be started in natural uranium, because the multiplication factor will always be below unity owing to the strong absorption of neutrons by the nuclei of uranium-238. And it is known that uranium-238 absorbs neutrons without producing many fissions.

There are, however, methods of initiating a chain reaction in natural uranium as well.

The problem is as follows: immediately after each fission of a nucleus of uranium-235 the neutrons must be slowed down to such an energy at which they will not be all captured by the nuclei of uranium-238. Then part of the neutrons slowed down to thermal energies will be able to bring about the fission of such a number of nuclei of uranium-235 as is needed to initiate a self-sustaining chain reaction, while the neutrons which had no time to slow down to thermal energies will be absorbed by uranium-238. Hence a new problem arose: to find such means or such a substance which would make it possible to slow down free neutrons to thermal velocities (of the order of 0.03 eV) without absorbing neutrons.

Neutrons can be slowed down only by making them collide repeatedly with atomic nuclei of so-called *moderators*. On

each collision the neutron should lose as much energy as possible.

From the laws of mechanics it follows that if the velocity of a moving body is reduced by elastic collisions with another, fixed or slowly moving body, then the greatest amount of its energy is lost to the other body if the masses of the colliding bodies are nearly or absolutely equal. Therefore in order to moderate neutrons it is best to use nuclei of light atoms, for instance those of hydrogen, whose mass is almost equal to the mass of the neutron. The best moderators as regards the combination of their properties—low absorption of neutrons, moderation efficiency, minimal cost and convenience in operation—are heavy water, pure graphite, and even ordinary distilled water. Effective moderation of neutrons is achieved in so-called *homogeneous reactors*, where the nuclear fuel is uniformly distributed in the moderator. In this case it is impossible to avoid intensive absorption by nuclei of uranium-238 of neutrons moderated to resonance energy (velocity). Therefore, for a chain reaction to be initiated, the amount of the fissionable isotope uranium-235 should be increased accordingly.

Reactors designed for producing plutonium use fuel elements made from natural uranium.

The spacing between the fuel elements is selected so that neutrons ejected in the fission of nuclei of uranium-235 are absorbed by uranium-238, but not all at a time. Part of the neutrons bumping into the graphite nuclei should get slowed down to thermal velocities (0.03 eV), by-passing resonance velocities (1-7 eV) and, penetrating the neighbouring uranium ingot, split the nucleus of uranium-235 without being absorbed on their way by uranium-238. Na-

turally, the great scattering of uranium-235 caused by this process requires a considerable increase in the amount of natural uranium necessary for the formation of a *critical mass*. To achieve this, several tens or even hundreds of tons of natural uranium have to be charged into the reactor. But even if all these conditions were observed, it would be very difficult to initiate a controlled nuclear fission chain reaction, since the fission reaction proceeding of its own accord develops so rapidly (within one hundred-thousandth of a second) that even the fastest-acting and supersensitive instruments cannot keep pace with it.

Quite unexpectedly, the so-called *delayed neutrons* came to the rescue.

The point is that the two or three neutrons ejected in the fission of uranium-235 appear not all at once, but at different times. The neutrons that are ejected first are *prompt neutrons*, comprising about 99 per cent of the total number of neutrons, and only later do the remaining 1 per cent appear with a delay of about 0.0001 sec to several tens of seconds. It is these delayed neutrons that made it possible to control the course of the nuclear fission chain reaction most reliably, not only with the aid of automatic devices, but even by hand. In this case the power of the reactor increases slowly enough and it will not "run away" under any conditions.

And finally one more, rather significant circumstance. Part of the neutrons originating in the fission of uranium-235 pass through the uranium and the moderator, and may simply escape outside without hitting a nucleus of the uranium. This loss of neutrons can be avoided by surrounding the reactor with a solid wall made of a good neutron reflector, for instance, graphite. After numerous collisions with

the moderator nuclei the neutrons will be reflected back into the reactor core. In this way the number of irretrievably lost neutrons will be greatly reduced. As a result it will be possible to reduce the nuclear fuel charge in the reactor accordingly.

Controlled thermonuclear reaction (nuclear fusion). A thermonuclear reaction is the union of nuclei of light elements to form heavier ones (helium), a type of reaction which has come to be known as *nuclear fusion.* The fusion reaction has so far been realized in the explosion of a hydrogen bomb of tremendous destructive power. Such an explosive reaction is not of great benefit to mankind. For this reason the scientists strive perseverently to achieve a controlled thermonuclear reaction, more precisely its deceleration to such a degree that it can be used for peaceful practical purposes, in the first place for the generation of electricity, because the energy released per unit mass of reactants in the fusion reaction is 8 times that liberated in the fission of uranium.

Core of the nuclear reactor. The part of the nuclear reactor containing a nuclear fuel, where a *controlled chain reaction of fission* of uranium or plutonium nuclei takes place.

Cosmic rays. Following the discovery of Röntgen rays (X-rays) in 1895, and later of radioactive radiation the scientists began to wonder whether there existed other, yet unknown radiations in nature which would shed still more light on the most obscure physical processes occurring in the infinite depths of the atom.

In 1912 a German physicist Hess launched a balloon carrying recording apparatus to a height of 5 km. To the surprise of the entire scientific world, radiation at high ele-

vations above the earth proved to be much more intensive than at the earth's surface. Numerous further experiments showed that the new radiation arrives from some other source in outer space (Cosmos) and it was given the name of *cosmic rays*.

The very first attempts to determine the nature of these rays brought many surprises and revelations.

To begin with, they turned out to be not rays, but particles—protons, a small number of helium nuclei—alpha-particles and, very seldom, nuclei of heavier elements: carbon, nitrogen, iron and others. Later these particles were found occasionally to possess colossal energies reaching millions of millions of millions of electron-volts, whereas the fastest and most penetrating particles ejected in radioactive disintegrations of substances achieve "only" 10 MeV. Cosmic particles were recorded even at a depth of a few kilometres underground or under water! Finally, what is most important, scientists established that the rays reaching the Earth contain no genuinely "cosmic" particles whatsoever. The overwhelming majority of these "rays" represent innumerable fragments of microscopic disasters—atomic nuclei of the air destroyed by primary "genuine" cosmic particles possessing such a tremendous energy that these fragments themselves turn into cosmic rays of nearly the same cosmic energy, capable of splitting atomic nuclei of the air just as easily. Even "fragments" of fragments of several generations of atomic nuclei smashed to smithereens are capable of splitting their own portions of atoms, building up an avalanche growing like a snowball—a peculiar chain reaction of nuclear disasters. And not only fragments. The great amounts of energy

released in such collisions give birth to whole families of new short-lived particles which do not exist under ordinary conditions and which, disintegrating, produce new particles having most diverse physical properties and characteristics. As if nature created, for 1,000,000,000ths of a second, her own "artificial particles", thereby inadvertently raising the curtain off the most deeply hidden secrets of the formation of matter (see *Elementary particles*).

Critical mass (of nuclear fuel). It is common knowledge that no force on earth can ignite a small piece of coal and make it burn on. At the same time a large heap of coal will burn marvellously. The cause of this seemingly incomprehensible contradiction lies in the fact that a chemical chain reaction of fuel combustion, which proceeds at 500 to 600 °C, can be self-sustaining only provided the heat released is capable of heating continuously the neighbouring layers of fuel to the same temperature. This is only possible when the influx of heat in the combustion zone exceeds its losses through the surface of the coal when it is still cool. And the smaller the piece of coal, the larger (relative to its mass) is its surface through which this heat can escape. For instance, in a ball 20 cm in diameter the surface-to-volume ratio is only 0.3, whereas in a small ball of diameter 2 cm the same ratio will be equal to 3, i.e., ten times as much! Naturally, the small ball when heated will lose 10 times as much heat as the large one. The losses may be so great that no self-sustaining combustion reaction will be achieved. A certain minimum physical mass of the fuel is required, which we will call the *critical mass*. For the initiation of a self-sustaining chain reaction of fission of uranium or plutonium nuclei it is necessary that

a spontaneously fissioned atomic nucleus eject, say, two neutrons, and these neutrons unfailingly hit neighbouring nuclei of the fissionable material and split two nuclei each, and these four nuclei eject four neutrons, which, in turn, split four nuclei and eject 16 new neutrons, and so on.

But neutrons may not hit nuclei of neighbouring atoms. The volume of 1 g of uranium equals 0.053 cm^3 and contains 2.56×10^{21} atoms. And if we add the nuclei of these atoms together they will occupy only 4.1×10^{-15} cm, or 10^{-12} of the volume of a uranium bead, or approximately the space occupied by a 1 cu mm ball as compared with the Sun. With this volume ratio the neutrons will hopelessly miss the target and escape outside the piece of uranium. No chain reactions of fission of uranium nuclei will be initiated.

But if we take a uranium block weighing a few tens of kilograms, for instance, a sphere 25 to 30 cm in diameter, then the probability of escape of neutrons that have missed all uranium nuclei on their way will be reduced to a minimum.

It is also possible to do the following: surround a uranium block with a material that effectively reflects neutrons—a reflector made of graphite, heavy water or other substances whose atomic nuclei are comparable with neutrons in respect to their mass. This screen will return the neutrons to the uranium block and thus offer them an additional opportunity to encounter a uranium nucleus at last and split it.

There is a third possibility as well. Nuclear particles moving with great velocities possess not only the properties of

particles, but also those of waves. The slower they move, the more pronounced their wave-like properties become; and what is most paradoxical of all, the larger is their so-called *cross-section*, i.e., the conventional surface of their possible interaction with nuclei they encounter on their way. The particle, as it were, increases in size, "expands". Where a fast neutron would fly through without hitting a single uranium nucleus, a slowly moving, "swollen" neutron will continuosly bump into uranium nuclei and split them without fail. Hence, it is necessary to slow down the neutrons in some way or other.

We can now draw our conclusions. In order to realize a chain reaction in uranium it is essential that its amount is not below a definite critical mass.

For specific conditions of initiation of a self-sustaining nuclear fission reaction the critical mass may have different values.

This can also be put as follows: the critical mass at which a fission chain reaction begins is the minimum amount of nuclear fuel with which each neutron generation gives birth to a next generation with the same or slightly larger number of neutrons, i.e., when neutron losses in the nuclear fuel owing to leakage or absorption by impurities are comletely replenished.

Crystal particle counters. These are counters of radioactive radiations which use the property of certain crystals to change their electrical conductivity when fast ionizing particles and gamma radiations pass through them (diamond, silver chloride, thallium chloride, and others).

Curie, c. Unit of measurement of natural or artificial radioactivity. One curie is the activity of a source which

undergoes 3.7×10^{10} disintegrations per second (the radioactivity of 1 g of radium). In everyday practice use is made of smaller units: millicurie (1 mcurie=0.001 curie), microcurie (1 μcurie=0.000001 curie).

Cyclotron. The accelerator of protons, alpha-particles, and deuterons, in which the particles are accelerated by an electric field of varying amplitude but constant frequency. The motion of the particles is controlled and they are focused by a magnetic field (which is also constant in time) set up by a powerful electromagnet. The frequency of the accelerating field is selected so that a particle moving by inertia inside one of two hollow semicircular electrodes, called *dees*, gets in the gap between the two electrodes each time at the moment when the electric field between them "whips" the particle, which gathers more and more speed with each half-circuit inside the dees.

The maximum energy obtainable with ordinary cyclotrons is limited to 25-30 MeV. This is due to the fact that at higher velocities (energies) of the particles the *relativistic effect* manifests itself—an increase in mass as the velocity of the particle approaches that of light, which disturbs the synchronization of the particle rotation in the dees with the arrival of the pulses of the varying electric field from the oscillator to the acceleration gap.

In order to increase the energy of the particles accelerated in the cyclotron various technical complications have to be introduced, such as, for example, artificial variation of the amplitude of the magnetic field set up by the electromagnet.

The cyclotron in which the field varies instead of the frequency of the accelerating voltage is called the *synchrotron*,

D

Decontamination. Methods and means for removal from clothing, equipment, various structures and areas, weapons and military equipment of radioactive substances which find their way there as a result of technological processes involved in the production and utilization of natural and artificial radioactive substances through negligence, accident or the use of atomic weapons.

Delayed neutrons. The process of splitting of an atomic nucleus of uranium-235 or plutonium-239 into two parts by bombarding with neutrons lasts about 1/1,000,000,000th of a second.

The fragments produced eject an average of two or three neutrons, which in turn can be used for splitting two or three other nuclei of fissionable materials, i.e., for initiating or supporting the self-sustaining fission chain reaction. Part of these neutrons (about 1%), however, are not emitted at once, i.e., within 1/1,000,000,000th of a second, but with a certain delay—from fractions of a second to tens of seconds.

The delay in one of the links of a fission chain reaction brings about a delay in the process as a whole. If the life of 99 per cent of each neutron generation is 10^{-5} sec and that of 1 per cent 10 sec, the average life of the entire set of neutrons will be 0.1 sec, i.e., 10,000 times that of the prompt neutrons.

Suppose we bring the *multiplication factor* precisely to unity, i.e., to the level where the neutron expenditure on the fission of uranium nuclei is continuously compensa-

ted for by the birth of other neutrons. In this case the chain reaction will actually be maintained only by delayed neutrons, since if it had not been for them the multiplication factor would have reduced below unity and the reaction would have gradually ceased. And if we wished to increase the factor now, say, to 1.001 or 1.007, the reaction rate would not jump up to an uncontrolled level but grow slowly within about 0.1 sec. This time will be sufficient to quietly insert into or withdraw from the reactor, even manually, control rods with neutron-absorbing materials, which preclude the overstepping of the dangerous limit of the neutron-multiplication factor, or allow the reaction to be stopped abruptly if need arise.

Deuterium, D. A stable natural isotope of hydrogen with an atomic weight of 2.0147 whose nucleus consists of one proton and one neutron, i.e., it is twice as heavy as ordinary hydrogen (protium).
Deuterium abundantly occurs in nature—one atom of deuterium per six thousand atoms of ordinary hydrogen. A six-hundredth fraction of the vast mass of water in the oceans consists of molecules of *heavy water*, which is a combination of two atoms of deuterium with one atom of oxygen.
Deuterium finds wide application in nuclear engineering, in particular as neutron moderator in nuclear reactors. Colliding with atoms of deuterium, neutrons are rapidly slowed down to thermal energies (velocities) due to the closeness of their mass to that of the deuterium nucleus. Ionized (free of electrons) deuterium nuclei are used in particle accelerators as heavy bombarding particles. Com-

pounds of deuterium, say with lithium can serve as a nuclear explosive in hydrogen (thermonuclear) bombs.
Deuteron. The atomic nucleus of deuterium (heavy hydrogen). It is the simplest nuclear system in nature consisting of only two particles, proton and neutron, bound by nuclear forces. The proton-neutron binding energy in deuterium is equal to 1.1 MeV.
Dissociation. Decomposition of a molecule into atoms or groups of atoms, for instance, under the influence of very high temperatures. The reverse process is called *recombination*, i.e., combining atoms into a molecule.

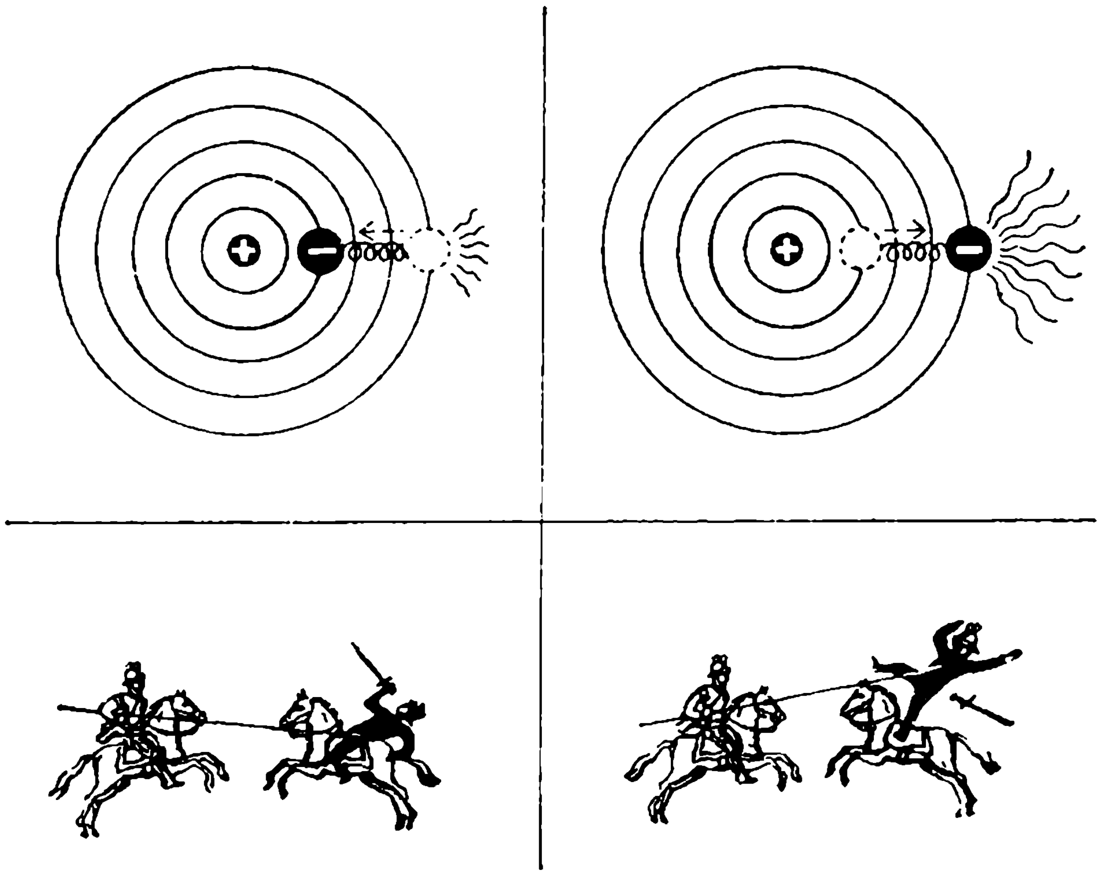
Dose. The amount of ionizing radiation absorbed by an irradiated object or part of it. This is so delicate a concept that several varieties of doses have to be established according to the medium, the type and nature of radiation. The *physical dose* is the energy of X-rays or gamma-rays absorbed by 1 cm^3 of air. The unit of measurement is the *röntgen* (*r*). Doses of ionizing radiations other than X-rays or gamma-rays (for instance, those of charged particles, neutrons) are measured by using the *röntgen equivalent physical (rep)*, i.e., radiation which is equivalent in its ionizing effect to one röntgen of X- or gamma-rays.
The physical ionization effect of alpha-, beta-, and other particles being the same, their action on living cells and organisms is different, therefore use is also made of the *röntgen equivalent man (rem)*, i.e., distinction should be made between the dose of gamma-irradiation, dose of röntgen irradiation, dose of mixed irradiation, neutron dose, etc.
As regards the irradiation of people and living organisms,

the *surface dose*, *depth dose* and *tissue dose* are also distinguished. Besides, distinction is made between the *local dose* (the dose referring to a certain limited surface spot or area) and the *dose acting on the whole organism*.
The *maximum permissible dose* of total irradiation of a man is a dose which, in the light of present-day knowledge, should not injure his organism appreciably at any moment in the entire course of his life.
In the Soviet Union the permissible single dose of total (integral) irradiation is 5 rem, after which the man shall not be subjected to irradiation for a long time. The maximum permissible dose of daily irradiation for people dealing with radioactive radiations is now 0.017 rem, and that of weekly irradiation is 1 rem.

E

Electromagnetic radiation. A complex physical process of transfer of energy from a region directly within the atomic system to the space surrounding the atom. A moving or oscillating electric charge naturally bound with some definite particle (electron, proton, meson, and so forth) sets up, with a change in its velocity, a changing magnetic field around it which in turn produces a changing electric field, and so on. The resulting varying electromagnetic disturbance, which comprises electric and magnetic fields successively merging into one another, spreads out further and further from the point of origin in all directions with

the velocity of light (300,000 km/sec), carrying with it a certain amount of energy.
This travelling electromagnetic disturbance is called an *electromagnetic wave.* In engineering, use is commonly ma-



de of the terms *frequency of electromagnetic oscillations* (obtained by dividing the velocity of light by the wavelength) and *wavelength*, expressed in metres or centimetres (obtained by dividing the velocity of light by the frequency of oscillations per second).
The most important fact is that the amount of energy carried by an electromagnetic wave is not the same, but grows

with oscillation frequency. This energy, expressed in ergs, is defined by the equation $E=h\nu$, where h is *Planck's constant* equal to 6.62×10^{-27} erg-sec, and ν the frequency of oscillations per second. Thus, the energy of an electromagnetic wave of violet light is twice that of red light.

Electron — "the atom of electricity." As man plunged deeper and deeper into the study of the properties of the objects surrounding him he encountered an ever-growing number of manifestations of electric forces. It was electrical energy that ultimately provided him with the most versatile and refined methods and means for solving extremely diversified problems of contemporary science and technology.

As we already know, each atom represents a whole system of interacting electric charges—positively charged nuclei and negatively charged electrons rotating about them. And since the bulk of the mass of an atom is concentrated in its nucleus, it appears that almost all existing matter is associated with positive electricity, which largely determines the properties of the world around us.

The difference between the chemical substances, for instance, oxygen and iron, is due solely to the fact that the atomic nucleus of oxygen contains 8 positive electric charges, that of iron 26, and the shells of their atoms contain the respective number of electrons. Most of the chemical reactions observed in nature are the result of interaction between outer electrons rotating at comparatively great distances from their nuclei.

For a long time the electron was considered the simplest and tiniest particle of the Universe. All electrons of all substances are completely identical, whether it is water, wood or iron. Under no circumstances has it been possible

so far to obtain or observe negative or positive electric charges less than the charge of one electron.

It was found during investigations that the laws of motion as established for large objects cannot be fully applied to electrons in the atom. Entirely different laws operate in bodies measured in one hundred-millionths of a centimetre. In contrast to the solar or any other huge mechanical system in which a body may move in any orbit depending on its initial velocity, the electrons in the atom are bound to move only along orbits which correspond to strictly definite values of their energy and magnetic moments. An electron can have no other energy values in a given atom. Such a discrete (discontinuous) nature of the location of electrons in orbits, or, more precisely, the possibility of existence of only strictly definite levels of electron energy and the impossibility of its having intermediate energy values in the atom, is one of the main properties following from the quantum theory. According to this theory the transfer of an electron from one orbit to another, i.e., from one energy state inside the atom to another, is accompanied by the absorption or emission of a light quantum of strictly definite energy. And if a certain orbit is already occupied by one electron it cannot be occupied by another electron; an atom cannot have two electrons in the same energy state. Of all the possible states which an electron may have in an atom, the first to change is the one at which it possesses the lowest energy and hence is most strongly attracted to the nucleus, i.e., is located in the innermost orbit.

Thus, electrons cannot all be concentrated in the same orbit, and each next electron occupies an orbit corresponding to a higher energy level and still remaining unoccupied.

This law is obeyed by the electron distribution in all the elements in the order of increasing energy or of their so-called *quantum state*.

The chemical properties of an atom depend on the number and arrangement of the electrons in the shell. Each period of the Mendeleyev Table is built according to the same law as the preceding one. Therefore the chemical properties of, say, the second period are close to those of the first period. The arrangement of electrons in the lithium atom is then reproduced—at a different energy level—in the sodium atom. In the next period we have a similar electron configuration in the atom of potassium, then in the atoms of rubidium, and cesium, and so on. All these elements belong to the first group of the Mendeleyev Table, i.e., to the group of alkali metals.

In order to tear the outermost electron away from an atom of, say, lithium, it is necessary to spend an energy equal to 5.39 eV. The other two electrons of this atom, which are located closer to the nucleus, are held more strongly. Their *binding energies* with the nucleus are 75.6 and 122.4 eV, respectively.

A directed flux of free (i.e., detached from their atoms) electrons in conductors or semiconductors is what we all know as an *electric current*.

When an atom absorbs energy arriving from outside (this energy being absorbed in strictly definite portions—*quanta*), electrons shift to orbits further removed from the nucleus (or to higher energy levels). The higher the energy of the quanta absorbed, the farther from the nucleus is the electron transferred.

In this so-called *excited state*, an atom cannot be left to

itself for a long time, and is forced to return to its *normal state* by shifting the electron back to the former place. The extra portion of energy acquired by the electron is emitted as a quantum of electromagnetic radiation. When this transfer occurs in the outermost orbits (where the electron-nucleus binding energy is the weakest) quanta of infrared rays, visible light or ultraviolet rays are emitted. When electrons jump over to orbits closer to the nucleus (for instance, skipping one or several orbits), quanta of "harder" electromagnetic radiation—*X-rays*, possessing an energy many times that of visible, ultra-violet and infrared light, are emitted.

Electron gun. A figurative name for a device used to obtain a directed electron beam in a vacuum. It differs from an ordinary electronic rectifying or amplifying tube (which has a heated filament or a heated cathode and an accelerating electrode) in that it has additional electrodes focusing (compressing) the electrons into a narrow pencil. The electron gun is most widely used in various cathode-ray measuring, indicating, and television tubes.

In nuclear engineering, the electron gun is used as the primary source of electrons for further acceleration in *betatrons*, *electron synchrotrons*, *linear accelerators*, and other devices where extra-dense electron beams are required.

Electrostatic forces. Forces of mutual attraction or repulsion acting between fixed or uniformly moving charges. In everyday practice these forces are comparatively small. But with the minute sizes and masses of microworld particles and very short distances of their interaction (100,000,000th and 1,000,000,000th fractions of a centimetre) these forces grow to amazing dimensions.

Elementary electric charge. The name given to the smallest electric charge in nature. It is equal to 4.8029×10^{-10} electrostatic unit and serves as one of the most important characteristics of any charged elementary particles: electrons, protons, positrons, mesons, and so on, no matter what electric charge they carry, positive or negative. The electric charge of a body can only be a multiple of the elementary charge and always represents the sum of the positive or negative elementary charges of the atomic particles making up the body.

Elementary particles. Today we do not any longer have to prove that all substances consist of molecules, the molecules of atoms, the atoms of a nucleus and electrons, and the nuclei of protons and neutrons. But what are the protons, neutrons and electrons composed of? These particles were named elementary, i.e., indivisible particles, assuming that with further division they may turn into anything but other particles.

About 10 years ago scientists launched a perseverent and systematic attack on the secrets of the structure of elementary particles, in the first place nucleons, i.e., protons and neutrons. As in nuclear physics in general, this work could proceed along two main lines. The first was to try and break up or crush, if possible, an elementary particle into constituent parts, if there were any. The only way to achieve this was to accelerate other, similar particles to velocities maximally close to the velocity of light and then shoot these "bullets" to bombard elementary particles in atoms of other substances, for instance, to use accelerated protons for bombarding nuclei of ionized hydrogen (also protons), to use protons and alpha-particles for bombarding

protons and alpha-particles, and so forth. The energies required for this (of the order of hundreds and thousands of millions of electron-volts) could be obtained only with the aid of powerful accelerators of charged particles. Machines accelerating charged particles to energies of tens of millions, hundreds of millions and finally tens of thousands of millions of electron-volts were at one time considered a great achievement.

The second way was to "probe" into the structure of elementary particles. This method is based on the familiar optical phenomenon: the smaller the object observed, the shorter should be the wavelength of light (electromagnetic radiation) illuminating this object. If the wavelength exceeds the length of the object, the wave will simply pass around it and we shall see nothing; if it is shorter, the wave will be reflected and we shall see the illuminated object. Therefore maximum optical magnification can be obtained by illuminating the object under study with ultraviolet rays invisible to the human eye but capable of being recorded on a photographic plate.

After de Broglie discovered that any very fast particles have wave-like properties it became possible to develop an electron microscope in which electrons accelerated to energies of 100 keV and over enable one to observe bodies only a few angströms in diameter (1 angström is equal to 10^{-8} cm).

According to the formula deduced by de Broglie, the heavier the particle and the faster it travels, the smaller is the corresponding wavelength. It appears that if a beam of electrons is accelerated to an energy of the order of several hundreds of millions of electron-volts, their wavelength

will become so small and commensurate with the sizes of nuclear particles that they can be used to "probe" into the structure of the atomic nucleus. The reflection and scattering of these waves serves to measure the nucleons making up the nucleus. And if an electron beam is accelerated to an energy of the order of one or two thousand millions of electron-volts, the wavelength of the electrons will become many times shorter than the nucleon diameter. Such waves would make it possible to establish the structure of protons and neutrons.

Ever since the scientists became armed with a powerful "atomic artillery" discoveries followed one after another, and in the first place new particles were discovered. An energy of millions of electron-volts proved to be sufficient to detect among the debris of "microdisasters" a positively charged electron—the *positron*. Accelerators of hundreds of millions of electron-volts made it possible to produce artificially *mesons*, which had first been found in cosmic rays. The development of high-energy accelerators (thousands of millions of electron-volts) led to the discovery of antiparticles—antiproton, antineutron, and other particles diametrically opposite in physical properties to ordinary elementary particles—the proton, neutron, etc.

Today we already know 16 elementary particles and about as many antiparticles. If we also include very short-lived particles, then the total number of known elementary particles will reach about 40!

Most of these particles are unstable. They disintegrate after a negligible period of time, turning (via a number of radioactive decays with emission of beta-particles) into a few, already stable particles of smaller mass: electrons,

protons, gamma-quanta, and neutrinos, or into their corresponding antiparticles, which are also stable in principle (see *Beta decay*).
As far as could be established up to now, none of the known elementary particles can be broken up into smaller constituent parts. They are all considered elementary particles because this implies that they have no structure.
The unstable particles are classified into two groups. One of them consists of particles heavier than the electron, but lighter than the proton. They are called *mesons*. The other group includes particles heavier than the proton. They are called *hyperons*. The hyperon decays only into *nucleons*. The following types of mesons are known: mu-mesons (μ-mesons), pi-mesons (π-mesons), and K-mesons. The mass of the μ-meson is approximately 1/8 of the proton mass, that of the π-meson about 1/7 and that of the K-meson about half of the proton mass. Mu-mesons can only be negative or positive. There is no neutral μ-meson. Apart from the mass, the μ-meson is evidently quite identical to the electron, and it may be regarded as a heavy electron. No other heavy electrons, however, are known to exist in nature.
The antiparticle of the negative μ-meson (μ^-) is the positive μ-meson (μ^+). Due to the existence of universal interaction a negative μ-meson should decay into an electron and two neutrinos ($\mu^- \rightarrow e^- + \nu + \nu^-$) with a half-life of 2.2×10^{-6} sec. Because of this interaction the three particles have much in common, and they are called *leptons*.
Pi-mesons may be negative, positive or neutral (π^-, π^+, π^0). The antiparticle with respect to the positive π-meson is the negative π-meson. Like the photon, the neutral π-

meson is identical to its antiparticle. The π-meson, which was predicted by the Japanese physicist Yukawa in 1935 (12 years before it was discovered) is responsible for the manifestation of the so-called *nuclear forces* in the atomic nucleus.

Nucleons continuously exchange particles. This is similar to the manifestation of electric forces which are due to the continuous emission and absorption of quanta of electromagnetic radiation by an electric charge. Pi-mesons can readily be obtained by colliding protons with an energy of several hundreds of millions of electron-volts. In this case the kinetic energy of nucleons is directly transformed into the rest mass of a π-meson.

A whole gamut of reactions are possible:

(a) proton + proton = proton + neutron + positive π-meson;
(b) proton + neutron = proton + proton + negative π-meson;
(c) gamma-quantum + proton = neutron + positive π-meson;
(d) gamma-quantum + proton = proton + neutral π-meson;
(e) gamma-quantum + neutron = proton + negative π-meson,
and so forth.

The charged π-mesons produced by high-energy accelerators decay according to the following decay modes: *positive π-meson*$\rightarrow$positive μ-meson + neutrino or positron + neutrino; *negative π-meson*$\rightarrow$negative μ-meson + antineutrino or electron + antineutrino with a half-life of 1.56×10^{-8} sec. A neutral π-meson decays much more rapidly, but only into two photons with a decay period of about 10^{-8} sec.

One of the newly discovered elementary particles is the K-meson. We know positive and neutral K-mesons (K^+ and K^0) with their corresponding antiparticles: negative K- and neutral K^0-mesons. Due to its large mass the K-meson

has more diversified possibilities of decay. The decay period of a charged K-meson is 0.85×10^{-8} sec.
There exist three modifications of the *hyperon*, an elementary particle heavier than the proton. They are denoted by capital letters of the Greek alphabet: Λ (lambda), Σ (sigma), and Ξ (xi). All the hyperons decay into nucleons. Each hyperon has an antiparticle with the opposite sign. The world of elementary particles appears to be extremely rich both in the variety of particles and in the types of their interactions and mutual transmutations.

Energy levels. The *"planetary" model* of atomic structure (see *Atomic and nuclear models*) only very approximately describes the mutual arrangement of the nucleus and the electrons rotating about it. It will be much easier to describe the behaviour of electrons and their interaction with the nucleus and the atom as a whole if we switch over from the pictorial concepts of shells, orbits, rotation trajectories, velocities, etc., to the concept of *energy levels*.
To each place in the space occupied by an electron rotating about its own axis and revolving around the nucleus at a certain distance from it there corresponds a strictly definite energy level. An electron can be at a particular level only if the amount of energy separating it from the energy level of another electron (and consequently the distance from the nucleus) is strictly equal to the radiation quantum or an integral number of quanta, but never to one-half, one-quarter, or any other fraction of a quantum. The arrangement of the electron shells and the distances from the nucleus are determined not by a certain strict geometrical construction, as for instance in crystals, but only by the

energy levels of the electrons located in the given shells. No two electrons can be at the same energy level.
An atom of any chemical element has a number of stationary states in each of which the electron shell possesses a strictly definite store (level) of energy. When the atom is in one of such stationary states, it radiates no energy. Such radiation is only possible by emitting integral numbers of quanta and only if the electron returns from one of the orbits corresponding to an excited state of the atom to an orbit corresponding to its normal, ground state. The energy of the emitted light quanta in this case is precisely equal to the difference between the initial and final energy levels.

Enriched uranium. A nuclear fission chain reaction can usually be initiated only in one of the natural uranium isotopes—uranium-235. This isotope, however, comprises only 0.72 per cent of natural uranium; the balance consists of uranium-238 (99.27 per cent) and a negligible amount (0.006 per cent) of uranium-234. Since the isolation of fissionable uranium-235 involves great difficulties and expenses, it is incomparably more advantageous both technically and economically to initiate a controlled chain reaction in uranium-235 without isolating it from natural uranium, with simultaneous conversion of a certain part of uranium-238 into plutonium. For purely technical reasons the reactor has then to be charged with a rather large amount of natural uranium, sometimes several tens of tons.
In some cases, however, for instance, for transportation purposes (nuclear reactors for sea-going ships, submarines, aircraft, etc.) the size of the reactor has to be reduced to a minimum in order to obtain very dense neutron fluxes, to

prolong reactor operation without recharging, and so on. In such cases the proportion of the fissionable isotope uranium-235 in the natural uranium charged into the reactor is artificially increased; the uranium-235 added is obtained by complex and costly separation of uranium isotopes at special plants.

This artificial increase in the amount of the fissionable isotope in ordinary uranium is called *enrichment*.

Exchange (strong) interaction. An interaction between two physical systems or particles as a result of continuous exchange between themselves and between them and some other, third particle common to both of them. For instance, nuclear forces acting between the nucleons of an atomic nucleus are due to the exchange of a particle called a π-meson between the nucleons (see *Nuclear forces*).

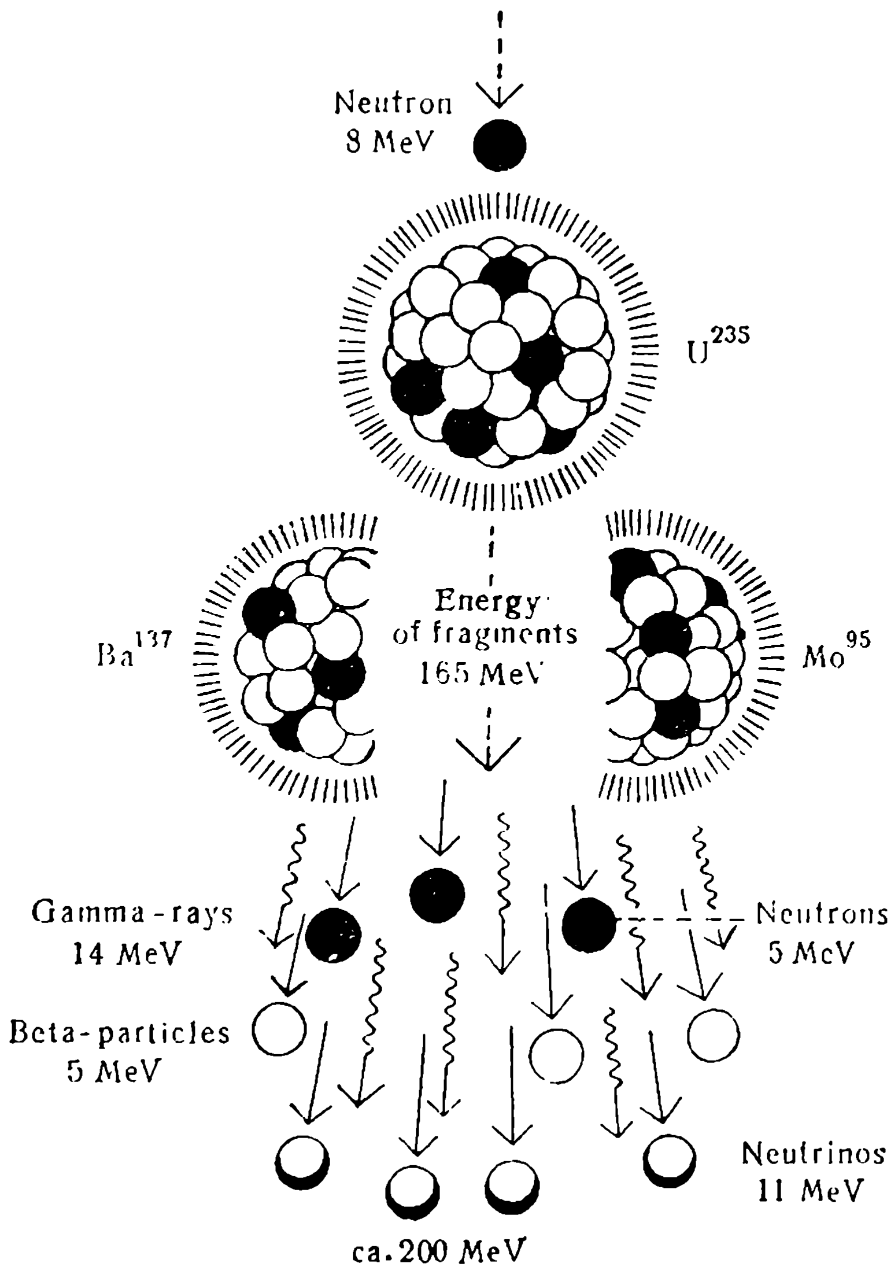
Excited state of an atomic nucleus. The state to which an atomic nucleus is brought when it absorbs a certain amount of excessive energy from outside as a result of colliding with or capturing some other particle.

F

Fast neutrons. Neutrons of energies exceeding 1 to 2 MeV. This energy level corresponds to the motion of particles at a temperature of several thousands of millions of degrees Celsius. At the other extreme are *slow (thermal) neutrons* of energy 0.03 eV.

Fission of an atomic nucleus. A special type of nuclear reaction in which nuclei of heavy elements, e.g. uranium or plutonium, become highly excited on absorbing a neutron.
After a short time they break up into two fragments (atomic nuclei of elements located in the middle of Mendeleyev's Periodic Table), ejecting a whole fireworks of particles: electrons, photons, gamma-rays or two or three fast neutrons. In this process the kinetic energy of the scattering fragments and other particles, which is equal to about 200 MeV, is liberated.
Several free neutrons, which happen to be superfluous for the nuclei of the newly formed atoms, can, under certain conditions, initiate their own chain of fission of neighbouring atoms of uranium or plutonium, due to which a self-sustaining nuclear chain reaction may begin in a block of these substances.
The fission of nuclei of heavy elements can be induced not only by absorption of neutrons, but also by irradiation with other particles accelerated to very high energies: protons, deuterons, alpha-particles, gamma-quanta, and others. However, only one type of fission has found wide industrial application, the one caused by irradiating fissionable materials with neutron fluxes in special units called *nuclear reactors* (originally named *atomic piles*).
There exists another kind of fission—so-called *spontaneous fission* of uranium nuclei which was discovered in 1940 by the Soviet physicists K. Petrzhak and G. Flerov. Here, some atomic nuclei of uranium break up into two fragments spontaneously, without any apparent external effect. This happens very infrequently, no more than 20 fissions per hour.

Under certain favourable conditions, however, which are usually provided in nuclear reactors, this proves quite



sufficient to initiate a nuclear chain reaction without resorting to some external (seed) neutron source.

In order to visualize more or less pictorially the mechanism of fission of the nucleus of a heavy element, say uranium, on absorbing a neutron, as far back as the 1930s the Soviet physicist Ya. Frenkel and the American physicist Wheeler proposed the so-called *liquid-drop model* of the structure of an atomic nucleus, which resembled in its behaviour a liquid drop charged with positive electricity. According to this model the particles—nucleons (protons and neutrons) of which the nucleus is made up—are arranged in the same fashion and in accordance with almost the same laws as the molecules in a spherical liquid drop.

Like-charged liquid molecules repel one another rather energetically and therefore the molecules are weakly bound with each other and are higly mobile, and the drop as a whole is liquid and tends to "swell", that is, to break up. The positively charged protons in a spherical atomic nucleus also repel each other and tend to fly apart approximately on the same principle.

But in a liquid drop other forces come into play as well. These are forces of surface tension of the external molecular film which retains and compresses the liquid molecules, due to which the liquid acquires the shape of a strictly spherical drop, the only possible shape for highly mobile and weakly bound particles.

The forces of surface tension, however, have a very limited range of action, which depends on the properties of the liquid—its density, viscosity, etc. Therefore the size of the drop cannot exceed a certain maximal value.

Here, too, we can find a very close analogy with the *nuclear forces* holding the nuclear particles, mainly protons, within the small volume of the nucleus and preventing them

from flying apart with a tremendous force. There is also a sharply defined limit to the range of action of these nuclear forces (about two nuclear diameters) beyond which even these exceedingly powerful forces fail to overcome the monstrous forces of electrostatic repulsion.

When a drop outgrows the volume within which the surface tension of the given liquid is capable of confining it, it breaks up under the effect of molecular electric forces of repulsion. But this is not done all at once: at first the drop deforms, elongates, then its middle part reduces in section, the drop assumes the shape of a dumbbell and finally splits into two parts.

Similarly, when an excess neutron gets into a nucleus the latter becomes excited. Owing to the energy brought in from outside, which is equal to 7 MeV, the motion of the particles making up the nucleus sharply increases, or, what is the same thing, the temperature of the nucleon substance drastically rises. The nucleus, which is expanded by the increased number of mutual collisions, "swells", so to say, and at a certain moment some of its parts "squeeze out", and the effect of the confining nuclear forces weakens. The equilibrium of the repulsion and compression forces in the nucleus is upset: the forces of repulsion of the protons begin to overcome the nuclear forces. The nucleus loses its spherical shape, elongates, reduces in section at some point and, turning into a "dumbbell", finally breaks up in two. Its two halves, which have become atomic nuclei of "middle" elements, fly apart with a tremendous velocity, carrying about 200 MeV of kinetic energy. Fission into three or four fragments is an extremely rare case.

The fragments, which are oversaturated with neutrons,

eject them and, after undergoing a number of successive beta-decays (neutron emission), turn into stable nuclei of "middle" elements of Mendeleyev's Table.

Fissionable materials. These are substances capable of entering into a nuclear fission reaction when irradiated with neutrons. Such properties are characteristic of uranium-235, uranium-238 (when irradiated only with fast neutrons of energy exceeding 1 MeV), plutonium-239 and the isotope uranium-233, which are obtained artificially in nuclear reactors (uranium-233 is produced by irradiating thorium-232 with neutrons). The fission of uranium-235, plutonium-239 and uranium-233 makes it possible to realize a *self-sustaining nuclear fission chain reaction.*

Free path of a particle. The distance between two consecutive collisions of a particle with other particles in the course of its motion in a medium, for instance, in a gas.

Fuel element. The basic and most important unit of the nuclear reactor with the aid of which nuclear fuel is introduced into the reactor core and heat is removed from the reactor.

A conventional fuel element consists of a cylindrical core containing the fissionable material, and a metal jacket. The main concern of nuclear reactor designers is the development and utilization of such materials for fuel elements which would retain as long as possible their mechanical strength, physical properties, and geometric dimensions at high temperatures and mechanical stresses, intensive neutron bombardment and powerful gamma-radiation.

G

Gamma flaw detection. A method for locating defects in metal ingots, castings, welds, etc., by irradiating them with high-energy X-rays and gamma-rays emitted by natural and artificial radioactive substances. At present this method of control is widely used in most diverse branches of industry and construction.

A gamma-source is installed at a definite distance on one side of the product to be inspected, and a detector recording the radiation (in most cases, photoemulsions) is placed on the other side. Depending on the thickness, composition and density of the relevant portion the intensity of radiation that has passed through the product will be different, and this will be recorded in the photograph together with all the possible defects (flaws, cracks, pores, unpenetrated welds, faulty assembly, foreign objects, ruptures, and so forth). The choice of a radioactive isotope is mainly determined by the thickness of the product irradiated, the density of the material, the sensitivity of the radiation detector used, the specific conditions of work, and other factors.

The use of gamma-rays for flaw detection requires strict observance of rules for handling radioactive materials and their storage and of safety regulations both by the personnel and all people on the premises.

Gamma-rays. One of the types of radiation emitted by atomic nuclei of natural and artificial radioactive elements. Gamma-rays are high-energy electromagnetic radiation of

extremely short wavelength (1 A and less) and hence of exceedingly great penetrating power. They are emitted during the acceleration and deceleration of high-energy charged particles (see *Bremsstrahlung*), pair annihilation (electron-positron, proton-antiproton, etc.), spontaneous and artificial fission of uranium and plutonium nuclei, and in certain other nuclear reactions.

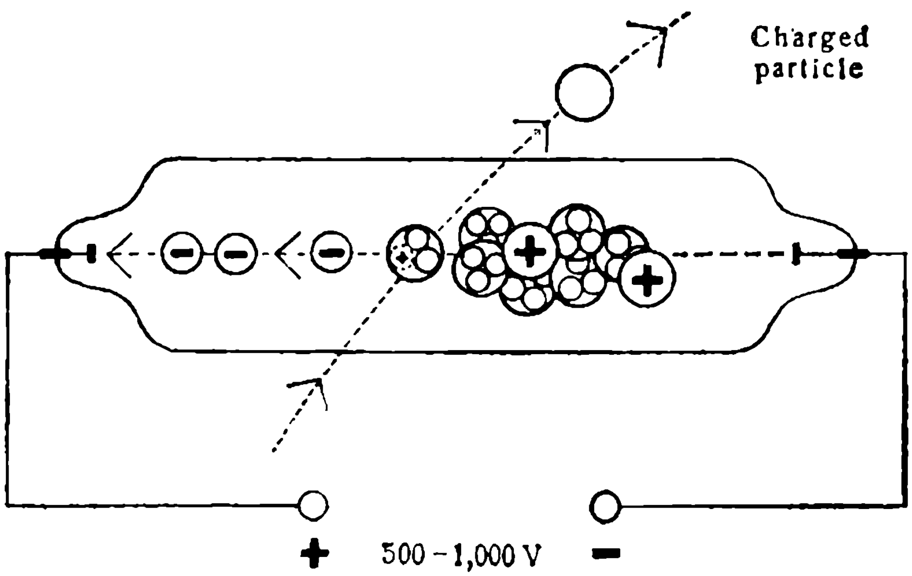
Since the wavelike properties (diffraction and interference) of gamma-rays are not pronounced, they are usually regarded as a flux of particles, gamma-quanta. The energy of gamma-quanta, however, increases with frequency of oscillations, which indicates their electromagnetic nature. The higher the frequency, the greater the energy the gamma-quanta carry.

Due to their high energy—up to 5 MeV in natural radioactive substances and up to 20 MeV in artificial nuclear reactions—gamma-rays not only readily ionize various substances, but are also capable of initiating certain types of nuclear reactions and, in particular, of producing electron-positron pairs and certain elementary particles. It is because of the hazard which gamma-rays present to people and other living organisms that nuclear reactors are surrounded with massive concrete walls—biological shielding, that natural and artificial radioactive substances are stored in containers with thick lead walls, and other complicated and costly protective devices are built.

Gamma-rays emitted by natural radioactive sources and arising in artificial nuclear reactions find wide application in science and technology. They are useful in the treatment of cancer, in revealing latent defects in big ingots of metal (up to 250 mm thick) and finished products in laboratories

and factories, in preserving and sterilizing foodstuffs and drugs, and in conducting research in many branches of contemporary science.

Geiger-Müller counter. The world of the atom and atomic phenomena is so small that it cannot be directly perceived by human organs. But the physicist has to distinguish one



particle from another, measure the energy, velocity, and direction of their motion, count the exact number of particles.

Considering the limitations of the cloud chamber, the German physicist Geiger designed a charged-particle counter which was later improved by him and Müller, also a German physicist.

The counter is extremely simple in design. This is a glass tube filled with a gas or a vapour at a pressure of about 100 to 200 mm of mercury, with a thin metal wire stretched along its axis.

A sufficiently high potential (500 to 1,000 volts) is applied between the wire and the metal shell of the tube. The wire usually serves as the positive electrode (anode).
A charged particle passing through the tube ionizes a tiny portion of the gas contained in it. The electrons knocked out of the gas atoms get into the strong electric field between the wire and the tube wall, and are accelerated to a very high velocity, breaking up the gas atoms into ions on their way. Second-generation electrons are also accelerated, ionizing new atoms, and so on. As a result, a whole avalanche of electrons is formed, whose impulse (current intensity) depends on the energy and velocity of the particle that first passed through the tube.
This impulse can be measured, and if it is too weak it is amplified prior to measurement. The sensitivity of such a device may be infinitely high. If necessary, it can detect even a single charged particle.
However, sensitivity alone is not sufficient for research purposes. Therefore, a particle counter, or more precisely an impulse counter, called a *scaler* is usually connected to the amplifier of the Geiger tube. A scaler is a rather complex device which sorts out the impulses automatically according to their energy, charge, velocity and direction, then counts them with the speed of a lightning.
This type of device makes it possible to detect and count the intensity of radiation of X-rays and gamma-rays, although these are known to be electromagnetic oscillations of very short wavelength rather than a flux of charged particles. Striking the metal wall of the tube, gamma-rays knock electrons out of the metal atoms. The electrons entering the electric field are accelerated and fly towards the central

wire, and then the process follows the same pattern as described for charged particles passing through the tube.
To determine the direction from which the particles arrive, "telescopes" are arranged—batteries of tubes with counters which operate only when the particle under investigation flies, say, from left to right, from top to bottom or in any other direction. A great variety of these devices are manufactured depending on the velocity of the particles, etc. They are very widely used in all branches of nuclear engineering. They are made large and small, stationary and portable, of low sensitivity for measuring large particle fluxes, and highly sensitive for detecting a single particle and prospecting for low-radioactivity uranium and thorium ores, and so on.

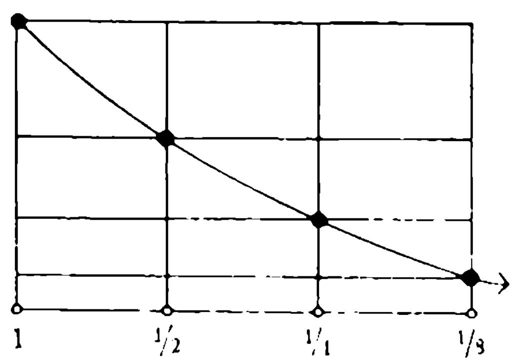
H

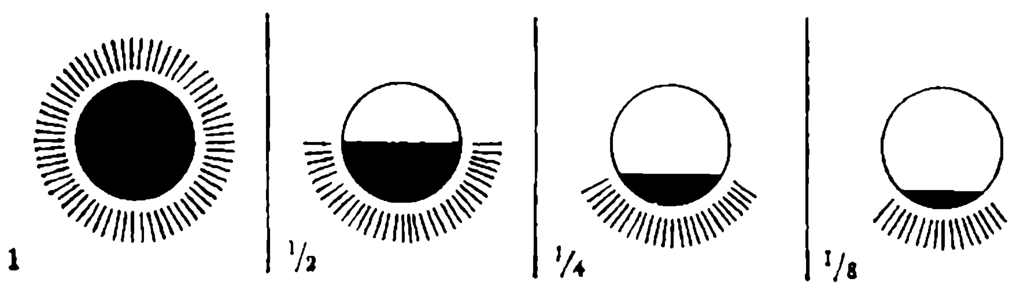
Half-life (period). An important quantity characterizing a radioactive substance is its *half-life*—the time during which half of the initial substance disintegrates. For instance, if half of the substance disintegrates within four days, its half-life is taken to be four days. Half of the remaining substance disintegrates within the next four days, so after 8 days only 1/4 of it remains, after 12 days 1/8, and so on. For radioactivity to drop to 1 per cent of that of the initial substance, about seven half-lives should elapse.
By saying that half of the atoms of a radioactive substance

disintegrate in a given period of time we only imply the average result. In fact, some atoms do not disintegrate at all, whereas others can decay within much shorter periods of time.

The more intensive the radioactive decay, the shorter the half-life. Strong emitters live much less than weak ones. One gram of uranium contains about 2.5×10^{21} atoms. However, of this astronomic figure only 12 thousand atoms

14,000,000,000 years	$_{90}Th^{232}$
4,500,000,000 years	$_{92}U^{238}$
24,410 years	$_{94}Pu^{239}$
1,617 years	$_{88}Ra^{226}$
3.82 days	$_{86}Rn^{222}$
3.05 min	$_{84}Po^{218}$
$3 \cdot 10^{-7}$ sec	$_{84}Po^{212}$





disintegrate per second. Therefore the half-life of uranium is extremely long—about 4,500,000,000 years. Thorium has a still longer half-life—14,000,000,000 years! The half-life of radium-226 is 1,617 years, radon—3.82 days, polonium-218—3.05 minutes, polonium-212—3×10^{-7} second. Some elementary particles have half-lives measured in 1,000,000th and 1,000,000,000th fractions of a second.

Heat. The molecules and atoms of the objects that surround us are constantly in a state of random motion and incessantly collide with each other. This motion, which is caused by the absorption of energy from the surroundings is called heat. The more energy is absorbed by the particles and the more intensive their motion, the more heat the given substance contains.

Heat exchanger. The water or vapour heated in the core of a nuclear reactor under a high pressure is simultaneously subjected to extremely intensive neutron radiation, and therefore the atomic nuclei of oxygen and the impurities, which are always present in water, become highly radioactive and hazardous to people. For this reason the vapour produced may be used directly in steam turbines of nuclear electric power stations provided only that all the working units of the steam power plant, as well as the reactor itself, are surrounded with *a biological shield*, a solid concrete wall several metres thick.

However, superheated water, vapour, hot gas, liquid metal and other heat-transfer agents can be passed through a heat exchanger, a device used to transfer heat from a hotter fluid to a cooler one. The simplest kind of heat exchanger is a coil placed in a hermetically sealed vessel. Passing through the coil, the hot fluid heats and vaporizes the water run through the vessel. As a result, the radioactive substances remain in the heat-transfer agent circulating between the reactor and the coil (the primary circuit) and will not get into the heat-transfer agent circulating between the heat exchanger and the turbine, or into the other devices. Therefore there is no need to provide bulky and costly biological shielding for all devices incorporated in the se-

condary circuit: steam piping, cooler, turbines, etc., although the presence of a heat exchanger increases the losses in the nuclear plant as a whole.

Heat-transfer agent. As the term implies, a heat-transfer agent is a medium serving to transfer heat. More specifically, the name is attached to a liquid or gaseous substance (water, vapour, gas, liquid metal, fused salts, liquid organic substances) which is passed through the core of a nuclear reactor to cool it and transfer the heat being removed to another heat-transfer agent, or else to be used directly in heat engines (steam, gas).

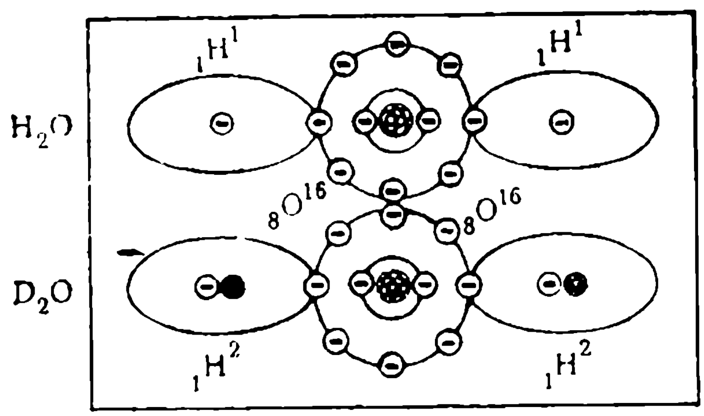
Because of the stringent requirements imposed on heat-transfer agents (low neutron absorption, chemical stability under intensive neutron and gamma radiation, low corrosivity during prolonged contact with structural materials of the reactor, high heat-transfer coefficient, high specific heat, low pressure at high temperatures) there are comparatively few substances capable of satisfying these high standards. Gases, such as carbon dioxide, are poor neutron absorbers, can be heated to high working temperatures, are safe in operation, but their heat conductivity is low. They have to be heated to high pressures in the reactor and a considerable part of the power obtained from the reactor has to be spent on pumping. The inert gas helium, which possesses high heat conductivity, is very scarce and expensive, and so is heavy water.

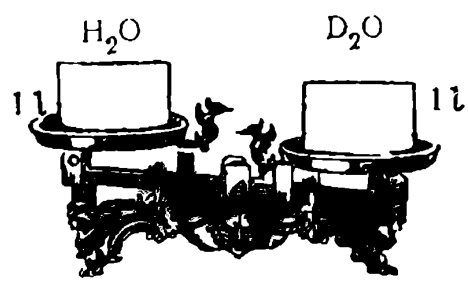
Liquid metals—sodium, potassium, lithium, bismuth, lead, mercury, and sodium-potassium and lead-bismuth mixtures—exhibit high heat conductivity. They permit obtaining very high temperatures at an extremely low pressure at the reactor outlet. Many of them, however, are highly

corrosive, explosive in combination with water and comparatively soon become radioactive as a result of irradiation in the reactor core.

For the reasons stated, the most common heat-transfer agents so far are distilled water and, much rarer, heavy water.

Heavy elements. A conventional name given to the chemical elements from polonium to uranium in whose nuclei the number of neutrons exceeds that of protons by 50 per cent or more.





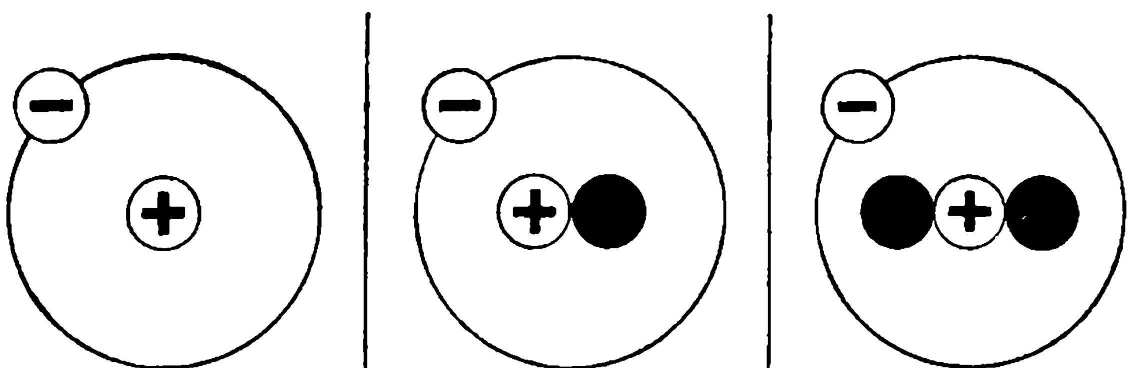
Heavy water (D_2°). The term commonly applied to water whose molecule (H_2°) contains two atoms of heavy hydrogen (deuterium) instead of two atoms of ordinary hydrogen. As contrasted with ordinary water, heavy water possesses

a number of curious properties. It freezes at +3.82°C instead of at 0°C, boils at 101.42°C instead of at 100°C and its density is 1.11 g/cm³. Seeds do not germinate in heavy water; plants, fish and animals die in it.
Heavy water is an excellent neutron moderator. In nuclear reactors it serves a dual function: as moderator and heat-transfer agent.
Helium, He. A chemical element with an atomic number 2 and an atomic weight of 4.004. It is an inert gas. Natural helium consists of two stable isotopes: helium-4 and a small amount of helium-3. The isotope helium-4 accumulates in nature mainly due to the disintegration of uranium, thorium, and other radioactive elements during which alpha-particles (atomic nuclei of helium stripped of all their electrons) are emitted.
Radioactive isotopes helium-5 (with a half-life less than 10^{-2} sec) and helium-6 (0.8 sec) have been obtained artificially.
The atom of helium consists of a nucleus and two electrons. The atomic nucleus of helium, which consists of two protons and two neutrons, is comparatively stable: the binding energy of all its particles is equal to 28.2 MeV.
Hot cave, hot laboratory. A specially equipped laboratory for handling highly radioactive materials.
All operations in such caves or large laboratories are carried out automatically or with the aid of remotely controlled manipulators operated by personnel reliably protected from penetrating radiations by biological shields many metres thick. These laboratories are also equipped with means for preventing contamination of the surrounding air with radioactive dust, aerosols and vapours in rooms where people are present.

Hydrogen, H. Hydrogen is the lightest and simplest chemical element, which is very widely distributed in nature, particularly in compounds, such as water. It also occurs in all living matter, in most organic compounds, especially in petroleum products, and in many gases found in nature. Traces of hydrogen occur in the atmosphere.

The atom of hydrogen consists of only two elementary particles: a positively charged proton and a negatively charged electron revolving about it.

Under normal conditions hydrogen is a gas. As with most other gases, its molecule consists of two atoms. The electron



Protium ($_1H^1$) Deuterium ($_1H^2$) Tritium ($_1H^3$)

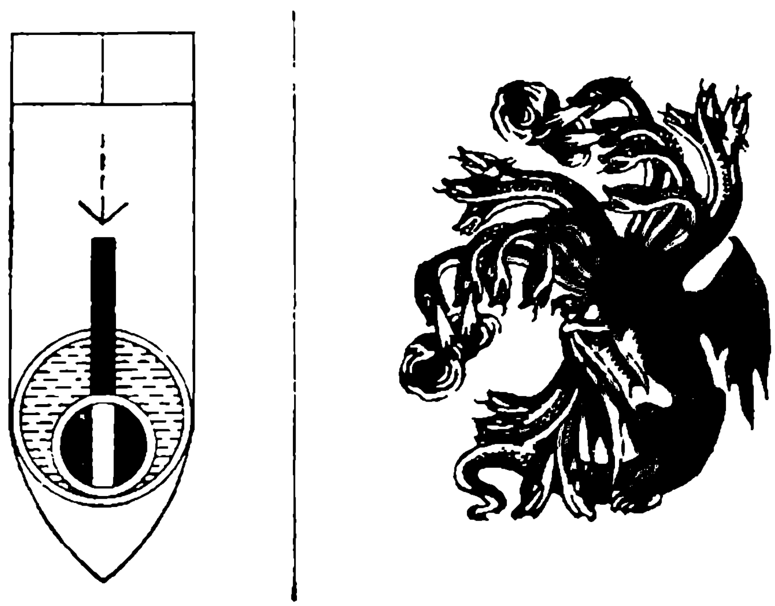
bond by which the two atoms are joined into a molecule is one of the strongest and most important bonds. In order to bring hydrogen into an atomic state, i.e., to break up its molecule into two separate atoms, it is necessary to spend a definite (quite considerable) amount of energy.

Two stable isotopes of hydrogen are known: light hydrogen ($_1H^1$), which is called *protium* and comprises 99.98 per cent of this element, and heavy hydrogen ($_1H^2$)—*deuterium*,

which does not exceed 0.015 per cent. The masses of these isotopes are 1.008 and 2.015 amu, respectively.
As a result of constant bombardment by cosmic rays, the Earth's atmosphere reveals negligibly small amounts of the radioactive isotope of hydrogen, emitting only beta-particles—*tritium* ($_1H^3$) with a half-life of 12.3 years. Tangible amounts of this isotope can be obtained only artificially in accelerators by bombarding deuterium or beryllium with a flux of heavy particles—protons and deuterons, or in nuclear reactors by irradiating nuclei of lithium-6 with a neutron flux. Having absorbed a neutron, lithium-6 disintegrates into two fragments: a nucleus of helium-4 (alpha-particle) and a nucleus of tritium.
Among the gases hydrogen possesses the highest heat conductivity and therefore it finds wide application in industry and engineering. The latest achievements in cryogenics enable liquid hydrogen to be used in most diverse fields of scientific research.
Hydrogen bomb (fusion bomb). A variety of atomic weapon of colossal destructive force. It uses the fusion of atomic nuclei of light elements into a nucleus of a heavier element (see *Thermonuclear reaction*) in which a tremendous amount of energy is liberated. A mixture of deuterium (heavy hydrogen) and tritium (superheavy hydrogen) is believed to be the most efficient for the purpose. The fusion of a nucleus of deuterium (deuteron) with a nucleus of tritium (triton) produces a nucleus of helium with a release of 17.6 MeV of energy, about eight times the energy obtained in the fission of uranium or plutonium. The temperature of several tens of millions of degrees necessary to initiate a thermonuclear reaction is achieved by exploding a sufficiently

powerful nuclear bomb inside the shell of a hydrogen bomb. (See picture).

Hyperons. In recent years, first in cosmic rays and then in particle accelerators, a particle was discovered, whose mass turned out to be greater than that of a nucleon (proton or neutron). This extremely unstable, fast-decaying particle was named the *superproton*, or *hyperon.*



The hyperon group includes 12 particles: one lambda-particle, three sigma-particles, two xi-particles, and their corresponding antiparticles (see *Elementary particles*). The neutral hyperon is relatively better known to scientists. Its mass is equal to 2,182 electron masses, i.e., it is about 340 electron masses heavier than the proton (lambda-particle). It decays in about 10^{-10} sec, giving rise to a proton and a negatively charged π-meson or to a neutron and a neutral π-meson.

I

Injection of particles. Prior to accelerating charged particles in various accelerators they should first be boosted to a certain energy level depending on the technical characteristics of the unit.

The rather complicated process of bringing such particles into the orbit of the main accelerator is called *injection*. Particles may be injected either from inside (in low-energy accelerators) or from outside the magnetic field of the accelerator (in units designed for maximal particle acceleration energies). Particles may be injected either continuously or in discrete pulses.

Intermediate neutrons. Partly moderated neutrons whose energy (velocity) ranges from 1 keV to 0.5 MeV (fast neutrons —above 0.5 MeV, slow neutrons—below 1 keV).

Ionization. In their normal state, i.e., when they are not acted on by external influences, atoms of a substance are as a rule electrically neutral, that is, the sum of the positive charges of all the protons contained in their nuclei is strictly equal to the sum of the negative charges of all the electrons revolving about the nuclei.

As a result of interaction with other atoms—in the course of chemical reactions, on strong heating, under the action of strong electric fields, light and other radiations—some atoms may lose one or several electrons located in the outermost orbits, while others, on the contrary, may capture excess, "foreign" electrons. Since that moment the neutral, "indifferent" state of the atom ceases to exist and it becomes

an electrically active ion: an atom that has lost a certain number of electrons becomes a positive ion, and one that has captured excess electrons becomes a negative ion. An electron detached from its atom and not captured by some other atom becomes a free electron.
The process of transformation of electrically neutral atoms into active ions is called *ionization*. In most cases the process of ionization of atoms involves a loss of electrons, i.e., the formation of positive ions.
Since the random thermal motion of atoms and molecules in a substance and consequently their collisions begin not at 0°C, but at absolute zero—0°K (—273.16°C), the ionization process also begins at that temperature. As the temperature rises, ionization gradually increases—almost imperceptibly in solids, more actively in liquids and vigorously in gases.
If an external electric field is applied to an ionized substance, then an orderly, directed motion of electrons starts in it, i.e., an electric current will flow through the ionized substance.
The degree of ionization naturally depends on a number of circumstances: the nature of the substance (e.g. its density and extent of rarefaction, if it is a gas), temperature, the energy of ionizing radiation and others.

Ionizing radiation. All types of radiation causing the ionization of atoms or molecules of a substance. They include visible and ultraviolet light rays, X-rays and gamma-rays, and charged particles—electrons, protons, alpha-particles, and multi-charge ions.
Ion-plasma jet engine (ion rocket). In connection with the

building of powerful charged-particle accelerators and plasma convertors of heat directly into electricity, work has recently been started on so-called *ion-plasma jet engines* for rockets.

The main attraction here lies in the possibility of first turning a gas fuel into a low-temperature plasma (ionization) and then accelerating the ions obtained to velocities comparable with the velocity of light, thus increasing the engine thrust by as many times, compared with the conventional types of fuel, as the exhaust velocity of the ion flux exceeds that of the combustion products of chemical fuel, if taken in equal amounts. Hence the increased payload, speed and range of ion rockets, the greater amount of fuel and other radical advantages.

The use of ion engines naturally requires sacrifices. In order to ionize the tremendous number of atoms of a gaseous fuel and then accelerate the obtained mass of charged particles to velocities of the order of tens and hundreds of thousands of kilometres per second, provision must be made on the rocket for powerful energy sources whose weight and size will "eat up" a considerable part of the advantages due to the great gain in exhaust velocity. However, calculations carried out by scientists show that the game is definitely worth the candle. As a result of many years of research ion-plasma jet engines developed in the Soviet Union were first used in the automatic interplanetary station "Zond 2" in 1964.

The design of the ion-plasma jet engine is extremely simple. Its principal part is an electrical generator which sets up a strong high-voltage electric field. Positively charged ions can be produced either from gas, for instance, hydrogen

and helium, the light metal cesium, or other substances capable of ionizing (i.e., losing their electrons) even at comparatively low temperatures of the order of 2 to 5 thousand degrees Celsius. When the ions get into the electric field of a powerful accelerator, they are accelerated to cosmic velocities and then ejected from the tail-end of the engine, building up a thrust.

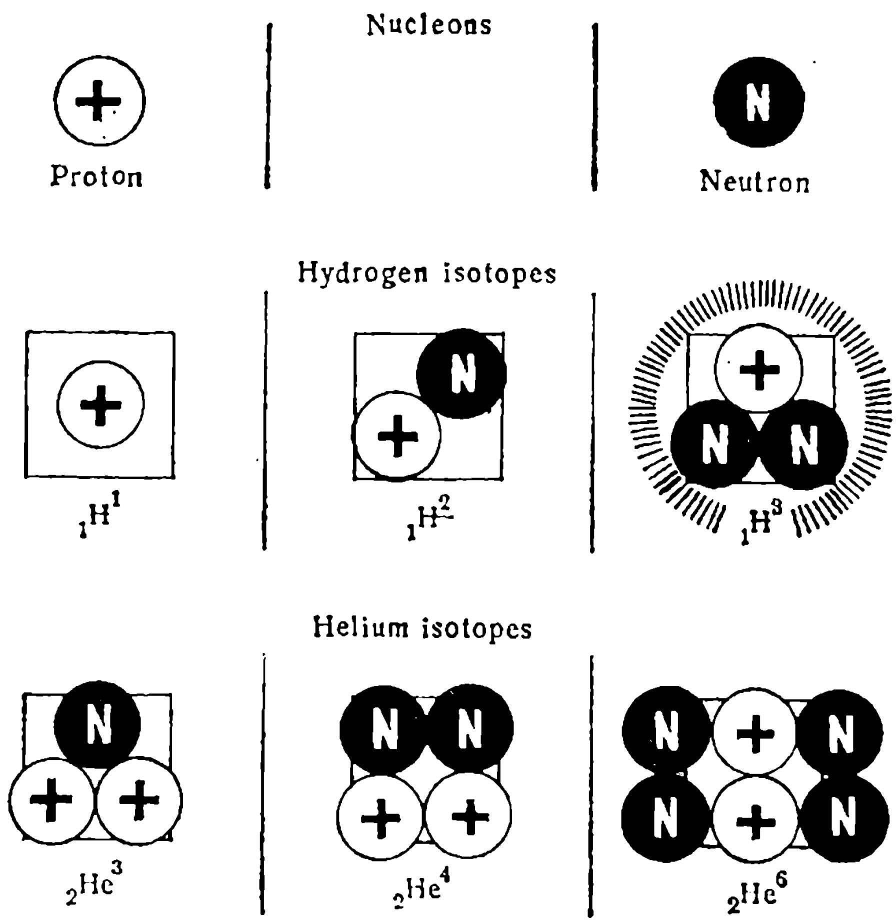
Isobars. This name was given to the nuclei of atoms having the same atomic weight but different positive charges (atomic numbers), and hence belonging to atoms of different chemical elements. A great number of both stable and radioactive isobars are known: for instance, zirconium-96 ($_{40}Zr^{96}$), molybdenum-96 ($_{42}Mo^{96}$), ruthenium-96 ($_{44}Ru^{96}$). They all have the same atomic weight (96), but different atomic numbers (40, 42 and 44, respectively).

Isomers, nuclear. Radioactive nuclei of atoms of certain elements may consist of one and the same number of protons and neutrons, which are differently arranged within the nucleus. Due to this property nuclei may achieve different degrees of excitation and on further disintegration they may possess different radioactivity as well, i.e., differ in their half-lives. For instance, atomic nuclei of the same artificial radioactive isotope of antimony—Sb^{124}—may have isomeric excited states with half-lives of 1.3 min, 21 min and 53.7 days, respectively.

Isotopes. In studying natural radioactive elements scientists encountered certain obscure phenomena.

Substances forming as a result of disintegration appeared to be entirely identical in their properties with the known chemical elements, differing from them only in atomic weight. For instance, ionium, a substance discovered in

1906, proved to be identical with thorium, and mesothorium, discovered in the following year, identical with radium. All the varieties of lead obtained as the ultimate result of successive disintegrations of the uranium, thorium and



helium series differ from each other and from ordinary lead only in atomic weight. Therefore in the course of gradual correction of the Mendeleyev Table of Elements several species of atoms of elements with exactly the same chemical properties but differing in mass had to be placed in the same boxes.

Such twin atoms came to be called *isotopes* ("taking the same place").

A natural question arose whether ordinary, non-radioactive elements also have isotopes. It was impossible, however, to isolate them by chemical means, because they are chemically identical. An electric field was also of no use, because the number of electrons in the orbits and the positive charge of the nucleus were the same, too.

What property of isotopes of the same elements could be used for their separation? Only one—the difference in the masses of individual atoms. But it could only be revealed during the motion of electrically charged ions in a strong electric or magnetic field. Given the same velocity, the path (trajectory) of an atom of a lighter isotope would deflect more distinctly than that of an atom of a heavier isotope.

This principle lies at the basis of a peculiar "atom-sorting machine"—the *Aston mass-spectrograph* named after the English physicist who first designed it (see *Separation of isotopes*).

It appeared that almost all chemical elements have isotopes. Some elements have few of them, others many. Thus, oxygen consists of three isotopes: oxygen-16 (99.76%), oxygen-18 (0.2%), and oxygen-17 (0.04%).

Isotopes may be *stable* and *unstable (radioactive)*, i.e., disintegrating spontaneously with time (see *Radioactive isotopes*). To date scientists have discovered more than 250 stable, more than 50 natural and over 1,000 artificial radioactive isotopes in 92 elements of the Mendeleyev Table!

The possibility of adding to ordinary chemical elements

their radioactive twins has opened up a wide vista for the application of such substances, which constantly announce their presence, in scientific research, particularly in biology, medicine, general and organic chemistry, and also in engineering and industry (see *Tracer atoms*).

J

Just chain reacting amount. The minimum critical amount of fissionable material which still permits of a self-sustaining nuclear fission chain reaction. In this case, each generation of neutrons, having fissioned a definite number of atomic nuclei of uranium, plutonium or thorium, gives rise to the next generation containing an identical or slightly larger number of neutrons (see *Critical mass*).

K

K-electron capture (K-capture). Apart from the two types of spontaneous (natural) disintegration of atomic nuclei of radioactive substances accompanied by the emission of beta-particles (electron disintegration with the ejection of an electron e^- and a neutrino carrying no electric charge, and positron disintegration with the ejection of a positron e^+ and a neutrino) (see *Beta decay*) we often encounter ano-

ther, entirely different, type of disintegration called *K-capture*. Here, an atomic nucleus captures one of its own electrons rotating in one of the innermost orbits. It is usually an electron from the K-orbit which immediately joins a proton and thus converts into a neutron. As a result we have an atom of an element one place to the left in Mendeleyev's Periodic Table (since one proton with a positive electric charge but with the original mass number has disappeared, changing to a neutron), i.e., its nucleus has become an isomer (see *Isomers, nuclear*) of that of an atom of a different element. For instance, an atomic nucleus of beryllium-7 may thus turn into an atomic nucleus of lithium-7.

K-capture is observed most frequently in atomic nuclei of heavy elements, because with an increase in the total positive charge of a nucleus its radius increases, whereas the radii of the orbits of the innermost electrons decrease, and thus the electrons move closer to the nucleus.

Since in a K-capture one of the electrons leaves the electron shell of the atom, this process of transformation of an atomic nucleus of one element into that of another is accompanied only by the emission of an X-ray quantum and a neutrino.

Kelvin temperature scale. The absolute temperature scale (^{0}K). It was proposed by the English physicist W. Thomson (Lord Kelvin) and is adopted as a more accurate temperature standard for scientific research compared with the Celsius scale (^{0}C) used in Europe and the Fahrenheit scale (^{0}F) used in England and the USA.

The zero in this scale is the lowest temperature possible in nature, i.e., it refers to a certain theoretical state of matter at which, as was believed by Lord Kelvin's contemporaries,

the motion of its molecules ceases completely. The zero value was obtained as a result of studying the properties of gases at zero pressure. The zero point on the Kelvin scale corresponds to —273.15°C. The value of one division on the Kelvin scale is the same as that of one division on the Celsius scale, i.e., it is equal to 1/100 the interval between the ice point (273.15°K or 0°C) and the boiling point of water under normal atmospheric conditions (373.15°K or 100°C).

K-meson. An unstable, i.e., short-lived elementary particle with a mass 965 times that of the electron mass (see *Elementary particles*, *Mesons*). This particle is observed in cosmic rays and can also be obtained artificially on powerful particle accelerators. Three varieties of K-meson have been detected: positively charged (K^+), negatively charged (K^-), and neutral (K^0). The electric charge of the positive and negative K-mesons is equal in magnitude to the elementary electric charge (that of the electron).

Krypton, Kr. A chemical element (inert gas) in the zero group of Mendeleyev's Periodic System. Atomic number 36, mass 83.60.

The natural gas consists of a mixture of six isotopes, from Kr-78 to Kr-86 (see *Isotopes*). Still more isotopes, only radioactive, can be obtained artificially, since krypton nuclei comprise a considerable part of the fragments into which atomic nuclei of fissionable materials disintegrate during a nuclear fission chain reaction in a nuclear reactor. Natural krypton is widely used for filling electric incandescent lamps and gas-discharge tubes to increase their candle power. Radioactive isotopes of krypton are used in weak (signal) light sources which require no electric current for their operation.

L

Light elements. A conventional name given to the group of chemical elements from hydrogen to oxygen inclusive, in whose atomic nuclei the number of neutrons does not exceed that of protons.

Liquid metals in nuclear engineering. In the fission of an atomic nucleus of uranium-235 or plutonium-239, more than 3/4 of the energy released is carried away by two fragments, which fly apart with a great speed. If these fission fragments are slowed down abruptly, their kinetic energy is immediately converted into heat. Therefore at this stage of development of the power industry it is most expedient to use nuclear energy as a source of heat.

But modern engineering also demands advanced means for the transformation of energy. It should be remembered that nuclear energy has to compete with highly efficient steam-power installations. For instance, the efficiency of thermal electric stations with turbines operating on steam superheated to 600-650°C and at pressures up to 300-350 atm reaches 38-41%. And since the nuclear reactor is joining them in a race as a peculiar steam boiler, its characteristics should be at least as good as those of up-to-date steam boilers. Here, however, we encounter quite a number of difficulties.

The steam boiler is specially designed to withstand the tremendous pressures which develop in it. The metals and structural materials used have a definite mechanical strength and heat resistance which can be accurately calculated and predicted.

Many metals and other structural materials subjected to prolonged irradiation with powerful neutron and gamma-quantum fluxes sometimes abruptly change almost all their properties. Very high pressures inside a nuclear reactor cannot therefore be used so far.

In distinction to the steam boiler the reactor can develop any power, but only on one condition, namely that the tremendous amount of heat produced should be immediately removed from it, otherwise the uranium rods or their jackets will melt and the whole reactor will be contaminated with radioactive fission products and put out of operation.

But if the surface of contact of the heated parts (pipes) with the cooling medium (heat-transfer agent) in a steam boiler can be infinitely large, the surface of the fuel elements in the core of even large reactors is comparatively small. Consequently an abrupt increase in working temperatures of nuclear reactors is impossible.

Are there any radical ways to solve this contradiction which affects to some extent the fate of a grand-scale nuclear power industry? Would it be possible to raise the efficiency of the nuclear reactor to that of the modern steam boiler without developing excessive pressures inside it?

One of the methods is the development of more heat-resistant and stronger structural materials: metals, alloys, new substances. Another method consists in searching for new, more efficient heat-transfer agents.

In up-to-date, highly efficient and economical steam boilers, especially in compact units, more and more extensive use is made of liquid metals possessing high heat conductivity: mercury, sodium, potassium, bismuth, their alloys,

etc. Their advantages over water and gases as coolants are often tremendous or even beyond any comparison.
But this is not the most important point. Liquid sodium, for instance, boils at 800°C. This means that the heat can be removed from the reactor with the aid of a liquid metal at a pressure equal to atmospheric! Water heated to such a temperature and converted into vapour would develop a pressure of the order of 160 atm!
Due to its high heat conductivity the volume of the liquid metal needed to cool the reactor may be many times smaller as compared with water or gas.
Hence, the cooling of a reactor with liquid metals makes it possible in principle to greatly increase the working temperature inside the reactor and achieve a high enough efficiency of the entire power plant.
Installations using liquid-metal heat-transfer agents have been built in the Soviet Union. They undoubtedly hold much promise.
Lithium, Li. A chemical element in the first group of the Mendeleyev Periodic Table. Atomic number 3, atomic weight 6.94. An alkali metal with a melting point of about 180°C, silvery-white, very soft. Occurs naturally in many minerals. On heating in air ignites at 200°C. Consists of a natural mixture of stable isotopes lithium-6 (7.52%) and lithium-7 (92.48%).
In nuclear physics the reaction

$$_3Li^7 + {}_1H^1 \rightarrow {}_2He^4 + {}_2He^4 + \text{energy}$$

is used to obtain alpha-particles of various energies. When lithium is irradiated with neutrons, the following reaction

takes place:

$$_3Li^6 + {_0n^1} \rightarrow {_1H^3} + {_2He^4}$$

as a result of which *tritium*, a radioactive isotope of superheavy hydrogen, is obtained.
Lithium hydride, LiH, is used for producing hydrogen. But if the ordinary hydrogen is replaced by deuterium in this compound, the resulting lithium deuteride, LiD, can serve as a nuclear explosive in a *hydrogen bomb*.

Logging, radioactive (geophysical investigation of boreholes). One of the most reliable means of investigating the geological structure of the earth's crust, and also of prospecting for useful minerals is to drill boreholes and to take rock samples from different depths. The rock sample (core) extracted from the drill rods indicates the composition and sequence of occurrence of the rocks. However, in deep drilling with casing pipes and with different filling of the borehole with water, drill mud, etc., for example, in petroleum prospecting, it is impossible to obtain a solid core. Therefore one cannot get an idea of the geological section of the borehole. But with the advent of highly sensitive devices for detecting extremely weak gamma-radiations, the geologists received a new, exceedingly precise, versatile and convenient tool for geophysical investigation of geological sections of boreholes, for prospecting and exploration of deposits of radioactive ores and waters and many other minerals, including petroleum.
This method is essentially as follows. As is well known, almost all rocks in the earth's crust contain negligibly small, but different amounts of radioactive substances. By lowe-

ring into a borehole a device which records gamma-rays emitted by different strata of rocks and easily penetrating casing pipes, and by recording the energy and time of their radiation, it is possible, by comparison with rock samples previously tested for radioactivity, to draw an extremely accurate geological section of a borehole of any length.

However, petroleum-bearing strata and aquifers do not emit gamma-rays and often their presence can only be surmised. Therefore, the passive method of investigation can be replaced by an active one. To do this, a rather strong neutron source is lowered into a borehole (neutron logging). As a result of intensive bombardment with neutrons the atoms of the elements of which the minerals are composed become radioactive and begin to emit gamma-rays—some more, others less intensively. A receiver of gamma-radiation installed at a certain distance from the neutron source is used to detect and measure the artificial radioactivity of the rocks.

Atoms of hydrogen, which are especially abundant in petroleum and water, are very good neutron reflectors. The number of reflected neutrons is an indicator of the depth of occurrence and thickness of petroleum-bearing strata and aquifers. Similar methods may be applied in many other branches of geophysical research.

M

Manipulator. An intricate device which enables an operator to carry out, by remote control, any manipulations with radioactive materials surrounded with a massive wall of biological shielding. Manipulators may be simple (manual), mechanical with a hydraulic or electric drive, or automatic. They are so designed that the tongs which are in direct contact with "hot" radioactive materials precisely duplicate the movements of the hands and fingers of the operator. They enable him to hold objects (test tubes, tools, even grains of various materials), move them from place to place, and weigh them, pour liquids, mix different substances, and carry out other operations.

Mass defect. In 1932 the British physicist Cockcroft and the Irish physicist Walton, his co-worker, bombarded a target of lithium-7 with a beam of accelerated protons, hoping to reveal something new and interesting. The photographs made in a cloud chamber showed that some nuclei of lithium-7, having absorbed a proton which hit them, disappeared, ejecting two alpha-particles, i.e., turning completely into two atomic nuclei of helium-4.
This event can be written thus:

$$_1H^1 + {}_3Li^7 \rightarrow {}_2He^4 + {}_2He^4$$

The result was virtually amazing! But it was a different thing that literally swept the scientists off their feet. When

they took a pencil and tried to strike a balance of the masses and energies of all the particles that took part in this seemingly very simple nuclear reaction, they revealed quite incomprehensible "gains" and "losses".

The total mass of the particles that had participated in this reaction was equal to 7.0182 (nucleus of lithium-7) + 1.0081 (proton) = 8.0263 amu, whereas the mass of the two separate alpha-particles obtained, when added together, yielded only $4.004 \times 2 = 8.008$ amu. How could one explain the disappearance of a mass equal to $8.0263 - 8.008 = 0.0183$ amu?

At the same time, and also "from nowhere", there appeared a very considerable gain in the energy of motion of the two scattered alpha-particles as compared with the energy of the proton which had initially split the nucleus of lithium-7.

Could it mean that the laws of conservation of mass and energy had failed?

Nothing of the kind. All this was precisely what should happen and was predicted theoretically as far back as 1905 by the greatest physicist of our age Albert Einstein, the creator of the theory of relativity—one of the boldest and most far-reaching scientific ideas of our time.

One of the most important results of this theory was that no body can move in a vacuum with a velocity equal to that of light—300,000 km/sec—or exceeding it. This statement ran counter to the then dominating Newton law of mechanics according to which the mass of a body is independent of its velocity and therefore any additional effort applied to a moving body should increase its velocity proportionally and hence infinitely. According to the theory

of relativity, however, one should distinguish between the rest mass m_0 and the mass m, which depends on the velocity of a given body. For low velocities the mass m is practically equal to the rest mass m_0, but if the velocity of the body becomes comparable with the velocity of light, the mass m increases very rapidly, tending to infinity. For instance, at a velocity of 282,100 km/sec the mass of an electron almost trebles; at 298,500 km/sec it increases by a factor of 10.79; a velocity of 299,400 km/sec makes the electron already 20.58 times as heavy, and so on. This leads to still another conclusion: any body can be accelerated to a velocity very close to that of light, but it can never reach the light velocity.
On the basis of the experiments carried out by the Russian physicist P. Lebedev, who had discovered light pressure, i.e., proved that light waves have a mass, and also on the basis of the experimentally confirmed fact that an electron becomes heavier when moving with a speed close to the velocity of light, as well as on the basis of other discoveries of our age, A. Einstein deduced his famous equation, which caused numerous arguments and misinterpretations, the equation relating mass (a measure of inertia) to energy (a physical measure of the motion of matter):

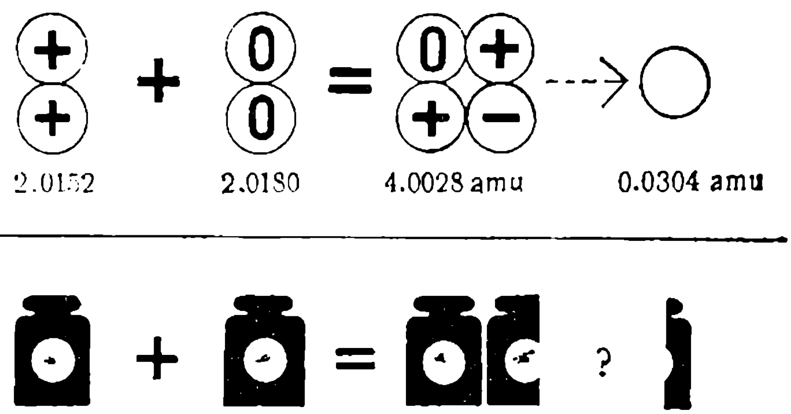
$$E = mc^2$$

that is, energy is equal to the mass of a body multiplied by the square of light velocity.
Consequently, any body possesses a definite amount of energy, which is strictly proportional to its mass and, conversely, to each material body having energy there cor-

:esponds a strictly definite mass. The greater the mass of ı body, the more energy it contains. By increasing the ›nergy of a body, for instance, by heating or accelerating t to near-light velocities we increase its mass as well. [f an excited atom of a substance emits a quantum of light 'photon), it loses a definite mass together with energy.
With all its abundant store of energy the atom gives it ıp extremely sparingly. To overcome the forces binding :he particles in the nucleus and resisting its rearrangement, ı certain amount of energy is required. Only then will :he disintegrating or rearranging atomic nucleus release the ›nergy as a result of the decrease in its mass. However, :he energy liberated on disintegration or rearrangement of ı nucleus does not necessarily exceed the energy spent on ts splitting or rearrangement. Hence, in order to obtain ›nergy it is expedient to break up or rearrange the nuclei ›f only those elements in which "losses" are smaller than 'gains". These are usually nuclei either of the lightest or ›f the heaviest elements.
\s is well known, the nucleus of helium (alpha-particle) s built up of two protons and two neutrons. To split such nucleus into its component elementary particles, it is ıecessary to overcome the tremendous attractive forces holling them together, which, as was found later, operate only vithin a distance of about two nuclear diameters.
'his can be done by hitting a nucleus of helium with a eavy particle accelerated to high velocity. In the Cockcoft-Walton device accelerated protons were used.
'hus, at this phase absorption of energy takes place. But s soon as the particles of the split nucleus fly apart to a istance exceeding two nuclear diameters, the nuclear for-

ces cease to operate and stupendous forces of repulsion of like-charged protons come into play.
The particles scattering with a colossal velocity possess an energy which is considerably higher than that spent on the breaking up of this atom.
Well, and what will happen if we try to join four nuclei of hydrogen (protons) together in order to obtain a nucleus of helium?
It would be logical to assume that at first we must spend a considerable energy to overcome the ever-growing repulsive forces of the four positive charges of the protons. But a still greater, virtually monstrous amount of energy will be released when the protons, having come closer together and entered the sphere of action of the nuclear forces of attraction, "fuse", as it were, into a new nucleus. Here, two protons will turn into neutrons by ejecting two positrons and two neutrinos. The final result will be the release of an excessive amount of energy accompanied by a certain decrease in mass. The difference between the mass of the particles before they were fused into a nucleus of a heavier element and the mass of the nucleus formed as a result of this reaction is called a *mass defect*.
Let us now do some calculating.
The sum of the masses of the nucleons participating in the reaction is equal to: 2 protons$\times$1.0076+2 neutrons $\times$1.0090=4.0332 amu; the mass of the nucleus of helium, which formed long ago from similar particles, is 4.0028 amu. The mass difference is 0.0304 amu. Nevertheless, even such a seemingly negligible decrease in mass is equivalent to an energy of 28.2 MeV!
The mass defect is observed not only when protons and

neutrons join together into atomic nuclei, but also when a nucleus of a heavy element splits into two lighter nuclei.
But not in all elements does the "liberated" energy exceed the energy spent when atomic nuclei are joined



together or fissioned. This only refers to a very limited number of atoms: to the lightest atoms—hydrogen, deuterium, tritium, helium, lithium, and to the heaviest ones—uranium, plutonium. None of the elements from the middle part of the Mendeleyev Table yields any gain in this respect. For this reason a cobblestone on the road, a piece of iron, silver, gold, mercury or other substance will remain what they are till doomsday. That is why an explosion of an atomic or hydrogen bomb does not cause detonation and explosion of all the substances and bodies around us: water, air, soil, the whole planet.
In the fusion of light elements the excess energy will be liberated only if all or a considerable part of the atoms present can be involved in the corresponding nuclear reaction. And even during the most powerful bombardment with the use of all the sources of heavy missiles at the dis-

posal of scientists—accelerated alpha-particles, deuterons and protons—hardly will a ten-millionth of them hit the target. All the others will miss it. That is why thousands of scientists in all countries of the world are seeking ways and means to interfere with the physical processes taking place in the depths of atoms so as to release the energy hidden in them by controlling some of these processes (see *Thermonuclear reaction*).

Mass-energy equivalence (relationship). One of the basic properties of any material body is its mass. In classical physics the term "mass" implied the amount of matter. Atoms were considered completely homogeneous, possessing no properties except "impermeability" and inertia, i.e., ability to resist external forces. The mass was regarded as the measure of inertia of bodies consisting of atoms. It was believed that the motion of a body does not in the least change its mass, that the mass remains absolutely constant in all cases of motion.

The Russian physicist P. Lebedev has laid the foundation of the theory of mass by proving experimentally that light exerts a pressure.

It is known from mechanics that the pressure exerted by a body on some other body is equal to the product of the mass of the former by the change of its velocity during the interaction with the latter. The discovery of light pressure suggested the idea that light, like ordinary bodies, should have a mass, as well as velocity. The mass was considered to be associated not only with ordinary bodies consisting of atoms, but also with light. Later the Soviet physicist S. Vavilov arrived at the conclusion that light pressure is equal to the energy of light divided by its velocity. If we

denote light energy by E, light mass by m, and light velocity by c, the following expression will obtain:

$$\frac{E}{c} = mc \text{ or } E = mc^2$$

Einstein's special theory of relativity has demonstrated that this equation holds good not only for light, but for any other kind of energy as well. Therefore it may be considered that in this formula E corresponds to any kind of energy, m to the mass of any material object, including light, and c to the velocity of light. This formula was given the misconceived name "mass-energy equivalence", which was soon afterwards interpreted by idealist physicists as a proof of conversion of matter into energy and vice versa. This interpretation does not, of course, reflect the real meaning of this law. The mass-energy relation expressed by this famous formula does not at all mean that mass and energy are equivalent or that they may convert into each other. It would be more correct to name this law the *mass-energy relationship*.

The equation does not assert that a mass m can be transformed into an energy E; it only states that an object of mass m simultaneously possesses an energy E.

The mass-energy equivalence principle shows the exact amount of energy corresponding to a given mass. To compute this quantity of energy it will be sufficient to multiply the mass of the body by the square of light velocity. Here the scientists stumbled on a breath-taking, amazing fact: a body possessing a mass of one kilogram contains an energy that could be obtained by burning about three million tons of coal! Suffice it to say that the harnessing of the ther-

monuclear reaction, which will relieve humanity once and for all of its worries about sources of energy, will enable man to liberate only one per cent of this latent energy, the reaction of fission of nuclei of uranium or plutonium will yield 0.1%, and the ordinary combustion reaction—only 0.0000001%!

Besides, the special theory of relativity has established the following relation between the mass of a body and the velocity of its motion

$$m = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$

where m_0 is the mass of a body or particle at rest ("rest mass"), m the mass of the same body or particle moving at a velocity v, and c the velocity of light. Since the radicand $1 - \frac{v^2}{c^2}$ is less than unity, the mass of a moving body always exceeds that of a body at rest (m_0). Thus, the formula shows that the mass is not constant and that it grows with the velocity of a body. And an increase in the motion velocity of a body also implies an increase in its kinetic energy. Consequently, an increase in the mass of a body with its velocity may be understood, in accordance with the above formula, as the dependence of the mass of the body on its kinetic energy. The greater the kinetic energy of a body, the greater is its mass. Having in mind this relationship, one can say that the mass of a body is the measure of the energy it contains. This mass-energy relationship is expressed by the equation $E = mc^2$. Here we should distinguish the mass of a particle at rest and the

mass which it acquires in motion. Hence the mass of a particle at rest was given a special name—the *rest mass*, or *proper mass*.

Light quanta, or photons, for instance, have no rest mass whatsoever, but they do possess a mass. The photons differ from elementary particles such as protons, electrons, positrons, also in that they have no electric charge and, besides, they cannot move with a velocity different from that of light.

Therefore, material particles (or bodies consisting of particles) which, unlike the photons, possess a rest mass, are usually referred to as *matter*. Photons have a zero rest mass, but they are no less material than particles of matter.

In the specific case of nuclear reactions, for instance, in the fission of an atomic nucleus of uranium or plutonium on absorbing a neutron, no changes will occur in the total amount of matter in nature.

Considering that the particles of the nucleus fissioned and the neutron that caused the fission were initially in motion and that the fission produced two unequal fragments and released several neutrons possessing high velocities, only the formulas for computing the energies and masses of the particles taking part in this event become more complicated. But the final result remains the same—the sum of all energies and masses after the reaction is precisely equal to the sum of all energies and masses prior to the reaction. Quite similarly, in *pair annihilation* (mutual destruction of an electron and a positron) it is convincingly demonstrated that the total energy and mass of the photon or photons produced is exactly equal to the total energy and mass of the "destroyed" electron and positron.

From the foregoing it follows that mass and energy are but two different properties of matter which are associated with its definite states.

Mass number. The number of nucleons—protons and neutrons—which make up the nucleus of an atom. Unlike the atomic weight, which is almost never an integer, the mass number is always a whole number close to the atomic weight of a given chemical element.

Mass of a moving body. According to the theory of relativity, the mass of a moving body is greater than the mass of the same body at rest (rest mass) and hence it continuously increases with velocity. For ordinary bodies moving even with a cosmic velocity, this increase in mass is so negligible that it cannot be measured by any of the existing devices. However, for atomic particles moving with speeds comparable with the velocity of light this increase becomes measurable. For instance, the mass of an electron possessing an energy of 1,000 eV and moving with a velocity of 18,720 km/sec increases by a factor of 1.002. With an energy equal to 1 MeV and at a velocity of 282,100 km/sec the mass increases by a factor of 2.957, and for an energy of 10 MeV and a velocity close to 299,400 km/sec the mass increases already 20.58-fold!

Mass-spectrograph. A device for determining the mass of charged particles which takes advantage of the property of particles to change the trajectory (path) of their motion under the influence of a strong magnetic field: the larger the mass of a particle, the less it will deflect. If a target is placed at the end of the path of such accelerated particles flying through a magnetic field, they will not hit at one point, but will form a strip in accordance with their mas-

ses, the lightest particles being arranged at one end and the heaviest at the other. The device is used for separating isotopes of chemical elements (see *Separation of isotopes*) and for other investigations.

Mendeleyev's Periodic Table of Elements. On the 6th of March 1869 at a session of the Russian Physico-Chemical Society D. Mendeleyev read for the first time his paper "Essay on a System of Elements Based on Their Atomic and Chemical Similarity".

The paper created a great sensation in scientific circles and brought a world renown to its author and Russian science, because it marked the beginning of a new stage in the development of science on the verge of the atomic age.

The young scientist (he was only 35 at the time) had racked his brains trying to detect any regularities in the world of chemical elements. And he was firmly convinced that they could be established only if all the chemical elements known at the time (many of them had not been discovered as yet) were arranged in a certain order according to their most important properties.

But what should then be considered the most important?

Mendeleyev chose the weight of the atom. Having recorded the atomic weight and chemical properties of the elements on the reverse side of his visiting cards, Mendeleyev persistently arranged them in thousands of conceivable and inconceivable combinations.

He began to see the light when he had divided the chemical elements arranged in the order of increasing atomic weight into horizontal groups. Elements similar in their chemical properties, when placed one under another, began

to recur, obeying a definite, evidently universal and simple law.

"... When I arranged the elements in accordance with their atomic weights, beginning with the lowest—D. Mendeleyev recalled later—it became obvious that there is a periodicity in their properties. I gave the name of the periodic law to the mutual relationships between the properties of the elements and their atomic weights; these relationships are applicable to all elements and they have a periodic nature".

At first Mendeleyev could not obtain strictly vertical columns. Then, being convinced of the existence of perfectly exact periodicity, the scientist made an extremely bold step. Wherever an element in a horizontal row could not be placed precisely under its chemical twin, he asserted that either the generally accepted atomic weights of the elements were wrong and should be revised, or there must be other elements yet undiscovered at the time. For these he simply left empty spaces in his Table. Moreover, knowing the "neighbours" above and below along the vertical line, Mendeleyev predicted with amazing accuracy the chemical properties of these missing elements.

This prediction of the great scientist found a brilliant confirmation. In 1875 the element gallium was discovered, in 1879 scandium, and in 1886 germanium.

This was the birth of Mendeleyev's famous Periodic Table of Chemical Elements, more precisely, the law of periodicity, which helped the scientists to penetrate into the most deeply hidden secrets of the atom.

The periodicity of the properties of chemical elements prompted the scientists some intriguing questions: is it really

correct to assert that the atom is an indivisible particle of the material world, the final step on the way to the microcosm? What lies at the basis of the difference in the atomic weights and the chemical properties of elements? Would it be possible to penetrate inside the atom itself, learn its internal structure? Do the regularities of the great periodic law extend to its structure? D. Mendeleyev himself said: "Naturally to-day it is impossible yet to show that the atoms of simple bodies are complex substances formed by the union of certain, still smaller parts". According to his notion, "the world of atoms is built in the same way as the world of celestial bodies, with its own suns, planets, and satellites".

The great law crushed the wall which had long separated chemistry from physics. Through the broad breach the knowledge was relayed further, this time to the investigators of the microworld.

Mesons. These are elementary particles whose mass lies between the masses of electrons and protons. They were first detected in cosmic rays and later produced artificially in interactions between particles accelerated to high energies. There are positively and negatively charged, and also neutral mesons. In absolute value the charge of positive and negative mesons is precisely equal to the elementary electric charge of the electron. The mesons are extremely unstable; they decay with a mean life of 10^{-6} to 10^{-14} sec.

The following meson varieties are known: positive and negative *mu-mesons* with a mass about 207 times the electron mass; positive, negative, and neutral *pi-mesons* with a mass

273 times that of the electron. The neutral pi-mesons have a slightly smaller mass. The positive, negative, and neutral *K-mesons* have a mass 966.5 times as large as that of the electron.

It is believed that the nucleons are held within the nucleus of an atom due to the constant exchange of pi-mesons between them. This exchange is responsible for the existence of the so-called *nuclear forces* which impart such an amazing strength to the atomic nucleus.

Moderation of neutrons. A neutron can be slowed down or moderated and made to lose part of its kinetic energy only through numerous collisions with atomic nuclei that do not absorb neutrons. For the maximum possible amount of energy to be lost in each collision, the mass of the nucleus of the moderator must be equal or close to the mass of the neutron. Besides, the moderator substance must be resistant to intensive irradiation (with neutrons and with other particles) and to high temperatures developed in nuclear reactors. For instance, ordinary and heavy water, helium, beryllium, graphite and certain other substances are excellent moderators.

Mössbauer effect. It is a well-known fact that an atomic nucleus, having absorbed a strictly definite portion of energy from outside, becomes excited—it deforms and pulsates. After a certain period of time it emits gamma-rays—high-energy photons with a high frequency of electromagnetic oscillations (see *Quanta. Quantum theory* and *Photon*), because the photons display the properties of both a particle and a wave. Scientists long attempted to use these oscillations for measuring time, since the constancy of the frequency of this radiation considerably exceeds that of

any other oscillatory processes. It is impossible even to imagine any other clockwork providing a precision of 1 sec in 100,000 years.

From the theory of nuclear processes it follows that the only receiver which responds to the gamma-quanta of radiation having precisely the same frequency are the nuclei of identical atoms. Having absorbed gamma-quanta, the atomic nuclei of the receivers should become excited and in turn emit gamma-quanta (again of the same frequency) after a fraction of a second.

In short, when one nucleus emits photons (gamma-quanta) and another absorbs them, both these "nuclear clocks" (the emitting nucleus and the absorbing one) give the same readings, for their frequencies precisely coincide. But as soon as these frequencies diverge, the phenomenon of resonance disappears. This indicates difference in time at the points of location of the emitter and the receiver.

For a number of reasons, however, this (resonance) absorption could not be detected for a long time—the oscillation frequency of gamma-radiation is too great and radiation time too short. It was not until 1958 that the German physicist R. Mössbauer succeeded in discovering the existence of resonance between the atoms of the radioactive and non-radioactive (Fe-57) isotopes of iron and later in measuring negligibly small periods of time with the use of this effect. This phenomenon could not be observed before Mössbauer's discovery only because the gamma-quanta emitted by the nucleus of the emitter were unable in most cases to excite the nuclei of the absorber; and they lost part of their energy in the course of radiation, owing to which their frequency was reduced. But why?

Let us draw an analogy. When a missile leaves the nozzle of a cannon, the latter suffers a recoil, i.e., a certain part of the energy received by the missile during firing is imparted to it. Similarly, a gamma-quantum ejected from an atomic nucleus imparts a recoil impulse to the nucleus that emitted it, losing at the same time a certain part of its kinetic energy, as a result of which its frequency reduces and the nucleus of the receiver is now unable to absorb such a gamma-quantum because the resonance conditions have been disturbed.

The situation can be remedied by making the emitter and receiver approach each other with such a velocity at which the frequency of the gamma-quantum (and consequently its energy) would increase to the resonance frequency. This is the so-called *Doppler effect*, which can be observed, for instance, when a train is passing. When a train approaches the observer, the frequency of oscillations (the pitch of the sound) of its whistle becomes higher than normal, and when the train recedes the pitch becomes lower than normal (the frequency is reduced). In the case of gamma-quanta the frequency changes by a fraction equal to the ratio of the velocity of the quantum motion to the velocity of light (300,000 km/sec). Therefore, a very high velocity of motion is required to obtain the necessary increase in the quantum frequency.

The energy loss by a missile, however, can be considerably reduced if the cannon is rigidly fixed on a base of great mass during firing.

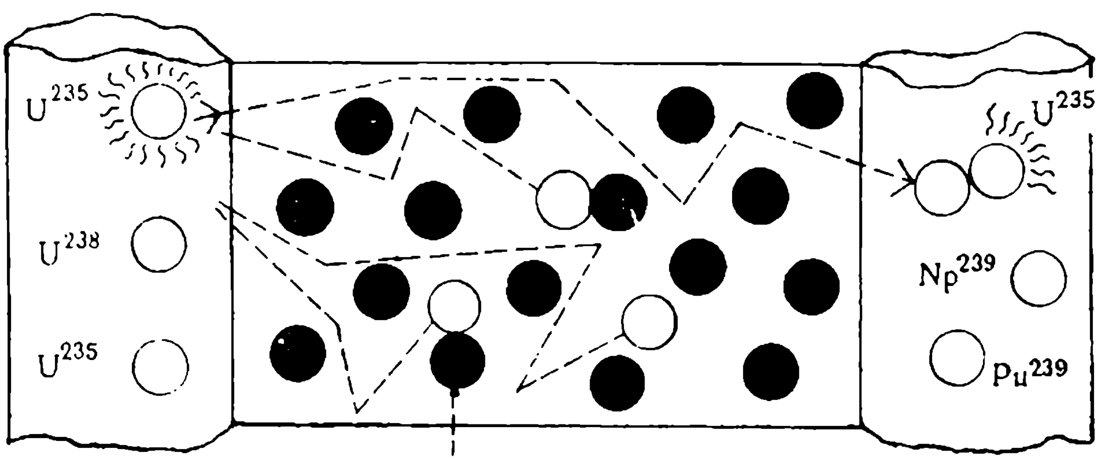
The effect named after Mössbauer consists in the fact that the recoil energy received by the atomic nucleus of the emitter during the emission of a gamma-quantum can be

abruptly reduced if the nucleus is bound to some great mass, for instance, embedded into a crystal. Then the recoil energy will be distributed among a large number of crystal atoms and will not cause any substantial displacement of these atoms, due to which the frequency of the gamma-quantum emitted will correspond to the resonance frequency of the nucleus of the absorber. The absorber nucleus itself can be fixed in a similar manner. Then the gamma-quantum re-emitted by it can be absorbed by some other nucleus or by the initial emitter.

The most important point in the discovery of the recoil-less resonance absorption is that it enables one to detect changes in the frequency due to the above-mentioned phenomenon (the *Doppler effect*), this time at a velocity of thousandths of a millimetre per second! This opens up opportunities for quite unexpected applications and makes it possible to observe phenomena which formerly seemed unobservable. For instance, as far back as 1911 Einstein, proceeding from his theory of relativity, predicted that the frequency of radiated light changes by a negligible value due to the action of gravity. To test this assertion, however, astronomic distances were required. The Mössbauer effect enabled the scientists to carry out this experiment by raising an emitter only 21 metres above the ground.

Multiplication factor (reproduction factor). In the fission of an atomic nucleus of uranium-235 into two fragments (elements from the middle of Mendeleyev's Periodic Table of Chemical Elements) two or three (on the average 2.5) neutrons are released. The number of fissioning nuclei will double or treble in each new generation of fissions. But this refers only to the ideal, theoretically possible case. In pra-

ctice, however, uranium of any degree of commercial purity always contains foreign impurities, which absorb a certain part of the neutrons released in fission. This loss can only be compensated for by minimizing the number of neutrons escaping from the reactor core, which have no time to fission their portion of nuclei of uranium-235, or by increasing the amount of nuclear fuel in the reactor (see *Critical mass*). But if the uranium is excessively "contaminated" with



harmful, neutron-absorbing impurities, then nothing can help—neither an increase in its amount, nor the presence of a good reflector returning the neutrons back into the reactor core. No chain reaction will be initiated in this case.

Atoms of the principal heavy isotope of natural uranium, uranium-238, also have to be considered as "harmful" impurities. Their nuclei absorb neutrons too avidly. Therefore a fission chain reaction cannot be initiated "just like that" in a solid block of natural uranium of any size, 99.3% of which consists of this isotope.

But how can it be done? If we succeed in initiating a chain reaction in a uranium block by some method, it will continue at the same level (the number of fissions per unit time) provided each neutron released in this fission unfailingly splits at least one nucleus of uranium-235. It is self-evident that an arbitrary quantity—the *multiplication factor* K (i.e., the average value of the ratio of the number of secondary neutrons effecting the fission of uranium or plutonium nuclei to the number of primary neutrons)—will be strictly equal to unity in this case. But with any, even the slowest increase in the number of fissions, say, when the number of neutrons fissioning nuclei of the fuel in each successive generation exceeds, even by one-millionth fraction, the number of the fissioned nuclei of the preceding generation, the multiplication factor will be above unity. Again, in the ideal case it will be equal, as is easy to guess, to 2.5-3.0, i.e., the number of neutrons ejected by the fissioned nucleus of uranium-235. One kilogram of uranium-235 contains about 2^{80} atoms. And even if the chain process in the block was initiated by a single neutron, all this literally astronomical number of atoms will fission within a negligible fraction of a second—only within 80 generations of fissions! And if the fission chain reaction is not slowed down artificially (i.e., if it is not controlled), it will terminate in an instantaneous explosion (atomic bomb). With the value of K less than unity no chain reaction is possible, and even if it began it would immediately die out.

Mu-meson (μ-meson, muon), An unstable elementary particle of a mass 206.86 times that of the electron. There are two kinds of mu-mesons: with a positive and a negative

electric charge equal in absolute value to the charge of the electron. The mean life of a mu-meson is about 2.2×10^{-6} sec, after which it desintegrates into an electron or positron and two neutrinos (or antineutrinos). Mu-mesons are formed mainly as a result of the disintegration of heavier *pi-mesons*. Unlike the other mesons, the mu-mesons interact weakly with nuclear matter and in most cases undergo only scattering on colliding with like-charged particles.

N

Neutrino. The history of physics of weak interactions is associated in the first place with investigation into the properties of, shall we say, the most mysterious of the elementary particles—the neutrino. The neutrinos are neutral particles which are difficult to detect and even more difficult to trap.

How did the scientists hit upon the idea of the existence of the neutrino?

During the experimental investigation of beta decay—spontaneous emission of electrons by atomic nuclei—it was found that the energies of the ejected electrons in this process had widely differing values. In most cases the electrons clearly lacked energy. The impression was that the lost energy disappeared somewhere, which contradicted the law of conservation of energy. The difficulties proved to be so serious that many physicists even proposed that the

law of conservation of energy be discarded. This "non-conservation" of energy, however, was of a rather strange nature. Indeed, if energy is not conserved in beta decay it could be expected that sometimes electrons should lack energy and sometimes they should have excessive energy, but this actually never took place.

This contradiction made the prominent Swiss physicist Pauli suggest in 1927 that there should exist a neutral particle with a mass much less than that of the neutron. The famous Italian physicist E. Fermi called this particle the *neutrino* (the Italian for a small neutron).

The arguments in favour of the existence of this particle were as follows. The seeming non-conservation of energy is due to the fact that the process of beta decay consists not only of the emission of electrons. A neutral particle which is not observed in experiments and which carries with it the "lost" energy is also emitted. And although a strictly definite total energy of all the particles is liberated in each process, it is so distributed among the decay products that in different cases the electron receives different portions of it. In 1942 the particle predicted by Pauli was detected. It proved to be in complete accord with the prediction: electrically neutral, with a negligible mass.

According to the theory of relativity the neutrino cannot be at rest because of its extremely tiny mass: it always moves with the velocity of light. As an elementary particle, the neutrino is in some respects similar to the photon.

It is well known that in the transmutation of particles not only the law of conservation of energy operates, but also the law of conservation of impulse. It has been established in numerous experiments that the total impulse in a beta

decay is not conserved if we do not assume the existence of the neutrino. The "elusive" particle carries with it not only the "lost" energy but also the "lost" impulse!

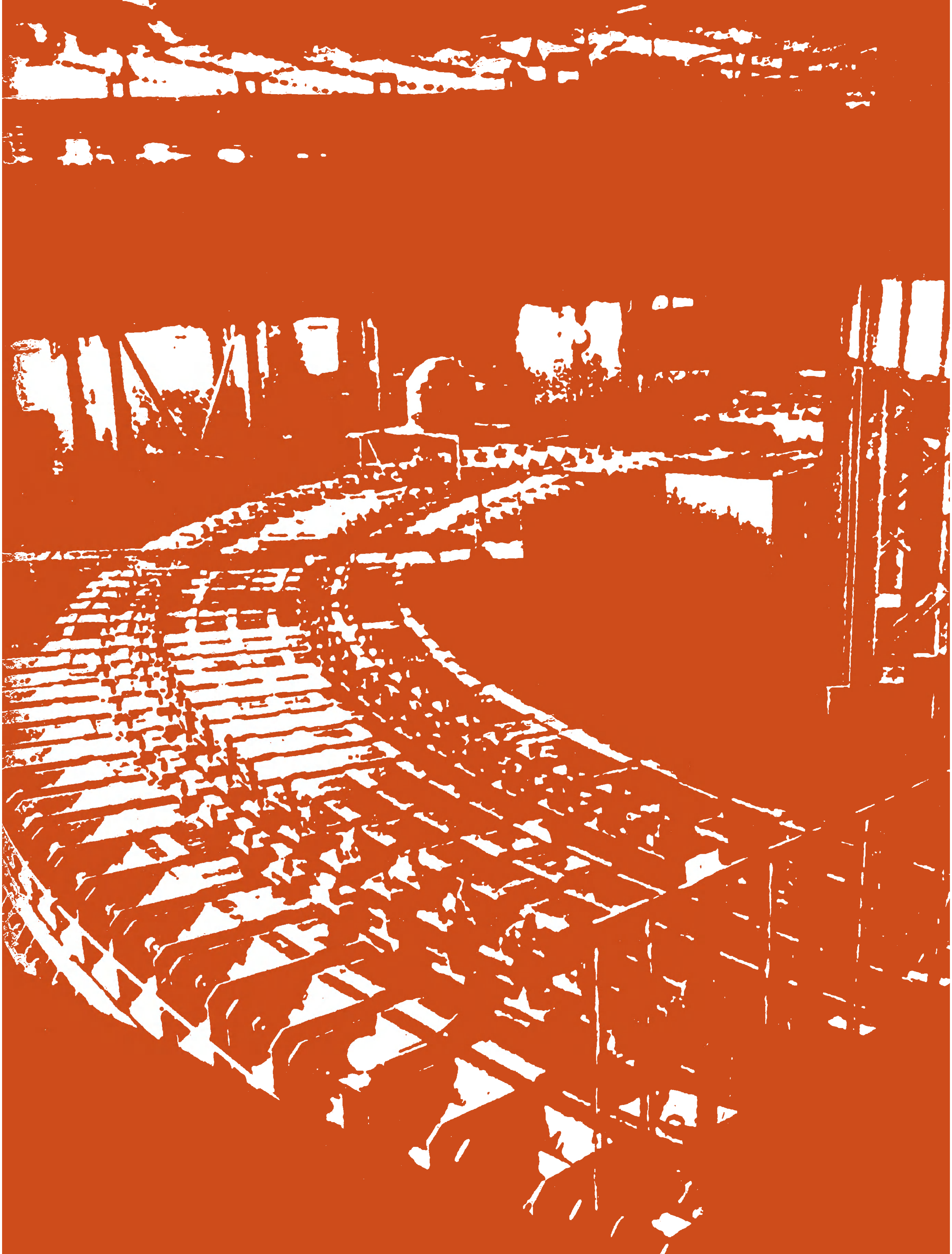
The non-observability of the neutrino was temporary and was due to the difficulty of its trapping and recording. It was not until very recently that scientists succeeded in catching a neutrino and recording nuclear transmutations caused by a free neutrino.

Recent years have witnessed the birth of a new branch of investigation of elementary particles, which is very important and interesting and on which the attention of all the scientists of the world is focused now—the physics of high-energy neutrinos (the founder of this theory is Academician B. Pontekorvo, the Lenin Prize winner). This branch is concerned with the study of the properties of the neutrinos of a "mesic" nature produced in the disintegration of mesons, the powerful beams of which can now be obtained on supergigantic accelerators.

But are the elusive particles, emitted in entirely different processes, identical particles? It appeared that the "electronic" neutrinos (those emitted in beta decay) differ from the neutrinos emitted in meson disintegration! Each of them, respectively, interacts only when paired up with a meson or an electron.

The idea of the universality of weak interactions received one more confirmation when physicists discovered a number of new, so-called "*strange*" *particles*. It turned out that "weak interactions" are characteristic of these particles too.

The existence of neutrino counterparts, antineutrinos 1 and 2 (electronic and mesic), was also predicted by analogy with



all other particles. Quite recently their existence was confirmed experimentally.

Neutron. In 1930 the German scientists W. Bothe and H. Becker were puzzled by the following phenomenon. When bombarding a plate of metallic beryllium with alpha-particles they discovered a very weak, but amazingly penetrating radiation ensuing from the target so that even lead shields tens of centimetres thick, which usually stopped the most powerful gamma-rays, failed to stop this radiation.

The talanted French scientists Irene Curie (daughter of Marja Sklodowska and Pierre Curie) and Frederic Joliot noted a still more curious fact. When a plate of paraffin wax—a substance rich in hydrogen—was interposed in the path of these strange rays, protons began to dart with tremendous velocities, and hence with a great energy, from the paraffin wax.

Alpha-particles were completely stopped by the beryllium plate and could not reach the paraffin wax, and even gamma-rays would be unable to knock 50-MeV protons out of the paraffin wax. What kind of superpowerful "artillery" was so unexpectedly discovered in beryllium and what "missiles" did it use to fire on the paraffin wax?

The English physicist J. Chadwick (a pupil of Rutherford), who had long studied the mysterious radiation, finally arrived at the only possible and correct conclusion: "These are not rays at all; simply the protons emerging from paraffin wax are set in motion by particles equal to the proton in mass but without any electric charge, either positive or negative". These particles were named *neutrons*.

Due to the absence of an electric charge any substance becomes "transparent" to the neutron. It easily overcomes all the defences of the atom: the outer electron shell, which vigorously repels any negatively charged particle, and the total positive charge of the nucleus, which thrusts aside even a heavy alpha-particle moving with a great velocity.

The discovery of the neutron dispelled the mystery surrounding the incomprehensible and "illogical" increase in the mass of atomic nuclei with an increase in their charge by just one unity and enabled the Soviet scientist D. Ivanenko and the prominent German scientist W. Heisenberg to propose in 1932 a new model of nuclear structure in which everything was surprisingly "simple and clear".

They believed that the nuclei of all atoms consist of protons and neutrons. The number of protons is equal to the *atomic number* of the element in Mendeleyev's Periodic Table, and the mass of all protons and neutrons taken together, to its *atomic weight*, or *mass number*.

For instance, the atomic nucleus of helium (the famous alpha-particle) consists of two protons which give it two positive charges (and accordingly two electrons in the shell), and two neutrons. The total number of protons and neutrons is four, i.e., precisely the atomic weight of helium, which had been puzzling the scientists for a long time. Similarly, the atomic nucleus of lithium contains three protons (atomic number 3) and three neutrons, which yields in toto the atomic weight of the element, equal to 6.

The discovery of the neutron gives a clue to still another puzzle—the existence of isotopes.

By way of an example let us take the simplest chemical element in nature, hydrogen, whose nucleus consists of

a single, positively charged proton. It is sometimes called *protium*. Then follows the heavy isotope of hydrogen, whose nucleus contains one proton and one neutron, and whose atomic weight is 2. This isotope of hydrogen was named *deuterium*. And finally, there is a very rare, superheavy and radioactive isotope of hydrogen with two neutrons and one proton in the nucleus. This isotope, called *tritium*, is almost never encountered in nature.

The new model of the nuclear structure, which we may have oversimplified to some extent, almost completely agrees with the numerous facts accumulated by physics and clears up complicated and involved contradictions. What is most important, it opens up a great number of ways and opportunities for invading the "sanctuary" of the atom—its nucleus—and craftily leads to new, more profound mysteries, contradictions and real miracles!

To enumerate these facts and wonders would be tantamount to expounding all contemporary nuclear physics from beginning to end. We will therefore restrict ourselves to information bearing more or less directly on the neutron.

For instance, why is it that the atomic nucleus, which contains, along with neutrons, positively charged protons, does not fall apart under the action of virtually titanic forces of repulsion of like charges (considering the small distance between them)? Only much later was it established that special, quite unique forces act strictly within the bounds of the nucleus; these are the so-called *nuclear forces*, which attract particles to each other, no matter whether they are charged or neutral. It was also found that these forces, acting over extremely small distances, considerably exceed the forces of repulsion of all protons taken

together. But for these forces, the nuclear particles would have long ago scattered in different directions—rather they would have never joined together.
But there are not and there cannot be any bodies in nature, even those the size of nuclear particles, that are not in constant motion depending on the particle energy, which in turn depends on the temperature of the substance made up of these particles. If an additional amount of energy is imparted to this system from some external source, the particles begin to move much more rapidly. And, naturally, a moment may come when this motion will become so vigorous that its energy will be sufficient for one or several particles to overcome the nuclear forces and escape beyond the sphere of their action. And then, under the action of forces of repulsion of like charges, the particle or particles will escape from the nucleus.
If a considerably greater amount of excess energy arrives, then all the particles of the nucleus, pushing each other still more energetically, will be capable of overcoming the mysterious barrier which bars the way for nuclear forces. And the nucleus will split of its own accord.
How much excess energy, or *excitation energy*, as the physicists call it, is required to achieve this?
The answer is: the heavier the atomic nucleus, the less energy is necessary. But the heavier the nucleus, the more energy is released in its disintegration (see table below).
The heaviest nuclei are the most unstable. And if we "push" them even slightly, i.e., impart to them a small amount of excess energy (5 MeV in our example), then the nucleus, saturated like a sponge, will divide on its own, using its own energy!

This can be done in two ways. The more difficult way is to try and "drive" into the nucleus some heavy charged particle capable of overcoming the resistance of the total positive electric charge of the nucleus.

Mass number of atomic nucleus	140	200	235
Energy required for its excitation, MeV	62	40	5
Energy released in fission, MeV	48	135	200

But an initial energy of 5 MeV is surely insufficient for a proton or an alpha-particle. The particles will spend most of it in overcoming the "armour"—the positive charge of the nucleus, and, having lost their strength, will not be able even to touch it, to say nothing of splitting it. Besides, natural radioactive substances do not emit heavy particles of even this energy. Consequently, they should be artificially accelerated to much higher energies and velocities by using special units—*particle accelerators.*

The neutron possesses quite different, literally amazing abilities. Since it carries no electric charge, it needs no energy to overcome the total positive charge of the nucleus. Taking advantage of its neutrality, the neutron easily approaches the nucleus, reaches the zone of attraction of the nuclear forces, and is drawn into the nucleus.

The nucleus, having absorbed the neutron, embarks on internal rearrangement. Now it possesses an excess energy equal to 7 MeV in the case of uranium-235, of which it should naturally rid itself immediately after it becomes excited. Thus, the mere addition of a neutron to the nucleus of a heavy uranium atom imparts to it an additional energy of 7 MeV.

Where does this excess energy come from? No miracles take place here, of course. After internal rearrangement of the old atomic nucleus into a new one the mass of the nucleus differs from the sum of the masses of the constituent nucleons. It is due to this difference in mass that an amount of energy equivalent to it appears (see *Mass defect*), which at first excites the nucleus and then causes its fission.

Thus it may seem that to do this the neutron does not have to possess any initial energy. It is only necessary to help it get into the nucleus of the appropriate atom, and there the neutron, mobilizing the latent energy reserves of the nucleus, will be able to liberate (true, with a slight loss of its mass) the energy capable of exploding the nucleus.

But neutrons, which do not possess any substantial initial energy, can split atomic nuclei of only those elements in which the excitation energy necessary for their fission is less than 7 MeV, i.e., just the energy that is liberated in the rearrangement of the nucleus caused by the extra neutron added to it. Such atoms are few: uranium-233, uranium-235, and plutonium-239.

Here, it would be reasonable to ask: where does the neutron get such unusual properties and abilities so sharply differing from the other nuclear particles, although the

latter also possess their own, amazing enough, properties?

The source of all these unusual features lies in duality, which was discovered at the turn of the century—the duality of the properties of light, which behaves both as particles and as electromagnetic waves. The scientists were still more excited when the same properties were discovered in the electron. These discoveries were dramatically explained by the theory advanced in 1900 by the German physicist Max Planck, according to which the process of emission of heat or light by a body occurs not continuously, but in discrete amounts—in packages of radiant energy, or *quanta*—and the light wave, which has a strictly definite length, sometimes manifests properties characteristic of particles.

In 1923 the French physicist Louis de Broglie established that specific wavelike properties are inherent in any moving particle. According to his theory the wavelength of any particle is directly proportional to a certain, very small quantity called *Planck's constant*, and inversely proportional to the product of the mass of the particle by its velocity. This relation is rather simple: $\lambda = \frac{h}{mv}$. It indicates that the greater the mass or the velocity of a particle or both, the shorter is its wavelength, and vice versa.

The laws of physics do not tolerate any exceptions. Therefore, an object of the macroworld, for instance, a missile or the Earth globe, along with the properties of particles, should also possess wavelike properties. But owing to their great mass the corresponding wavelength is so small that these wavelike properties can be completely neglected. To high-velocity neutrons there corresponds such a small wa-

velength that they actually behave as particles. Certain aspects of their particularly "strange" behaviour may be explained only by explicitly wavelike properties. But since the neutron mass is negligible as compared with any, even microscopically small body, its wavelength becomes quite a perceptible value in typical phenomena prevailing in the microworld.

For wavelike properties to manifest themselves prominently enough in the behaviour of a neutron, its velocity should be as low as possible. It can be slowed down to such an extent that the neutron will lose the properties of a particle altogether and will behave as a wave.

In the light of the foregoing it is naturally difficult to establish the actual dimensions of a neutron, since they, strange though it may seem, depend on the velocity of this particle. For instance, the diameter of an ordinary atom is approximately $(2\text{-}4)\times10^{-8}$ cm. The nuclear diameter is still smaller—about 10^{-13} cm. Finally, the proton diameter hardly reaches 2×10^{-14} cm. For the wavelength of a neutron to correspond approximately to the atomic diameter, i.e., 10^{-8} cm, its energy (i.e., velocity of motion) should equal only about 0.1 eV. A neutron of such small energy can be represented more accurately as a wave of length 10^{-8} cm rather than a particle of the same size.

But then paradoxes begin. A neutron of wavelength 10^{-8} cm turns out to be tens of thousands of times as large as a nucleus, which also contains neutrons, and not one but quite a few sometimes!

A neutron can be inside a nucleus only provided it moves with a high velocity and consequently has a short wavelength. And a high velocity, as we know, implies a high

energy. Therefore the neutrons, being constituents of a nucleus, have an energy of about 50 MeV to which there corresponds a very short wavelength, of the order of 10^{-13} cm. This circumstance made it possible to explain the mystery of beta decay of radioactive substances, which had long worried the scientists and messed up all their cards.

A neutron, having entered a strange atomic nucleus and being unable to resist the most complicated nuclear interactions, which are equivalent to monstrous temperatures, disintegrates into a proton and an electron.

It was this discovery that enabled the scientists to consider a proton and a neutron as identical particles. Hence their name—*nucleons*. They can only exist in one state, either protonic or neutronic.

In a beta decay one of the neutrons transforms into a proton. It is at this moment that an electron appears. Its charge must counterbalance the positive charge of the newly born proton.

However, in virtue of the laws governing the radioactive disintegration of unstable nuclei, the electron cannot find itself a place in an orbit and is forced to leave the nucleus. This electron will be what we call a *beta-particle*. The total positive charge of the nucleus, which remains unstable, becomes one unit higher.

The proton, in turn, may change into a neutron under certain conditions. But then its positive charge should disappear. And indeed this charge is carried away by a particle which is a precise replica of the electron, except that it has the opposite, positive charge. Such a particle was discovered in 1930 by the American physicist Anderson who named it a *positron*. Both these transformations are

accompanied by the emission of one more particle—*neutrino*, which was mentioned before.

Neutrons emitted by a beryllium source fly with a tremendous velocity. Consequently, their effective size, or, as it is called, "*cross-section*" is very small. Colliding with atomic nuclei of light elements which they encounter on their way, they rebound from them and change the direction of their flight in much the same way as billiard balls rebound from each other. Each such collision costs the neutron the loss of part of its energy, and therefore its velocity is slowed down, and its "size", or "cross-section", diminishes.

The scientists took advantage of this phenomenon to slow down the motion of a neutron by repeatedly colliding it with substances containing atoms whose mass is close to that of the neutron (hydrogen, helium, carbon). Without being able to "see" the neutron itself, it is easy to observe and measure the velocity and energy of all atoms "pushed" by it or rebounding from it, and thus find the velocity, energy and size of the neutron itself.

The neutron, as a particle, turned out just a tiny bit heavier than the proton. It is radioactive outside the nucleus and, having spent about 11.7 minutes at large, begins to disintegrate. Turning into a proton, it emits an electron and a neutrino.

The energy released in neutron disintegration is about 1 MeV. This explains why the neutron is slightly heavier than the proton.

Observing the behaviour of neutrons, scientists soon discovered one more amazing feature: though easily penetrating a thick steel armour, neutrons were unable to overcome even a thin cadmium plate which was easily pierced

not only by gamma-rays, but even by a flux of beta-particles (electrons).

The new "strangeness" was also soon explained.

The atomic nuclei of certain elements (cadmium, boron, hafnium, etc.), instead of repelling a neutron, "capture" it, draw it in. The slower the velocity of the neutron, the more successful is the capture.

Nuclear electric battery. A device converting atomic energy directly into electric current, by-passing numerous "intermediaries": steam boilers, steam piping, heat-exchangers, turbines, current generators.

The simplest battery consists of two plates: a pure beta-emitter, strontium-90, and a semiconductor, for instance, silicon. The beam of fast electrons emitted by the strontium passes through the semiconductor and knocks out of it a great number of additional electrons—tens and hundreds of thousands times as many as there are in the stream given off by the radioactive isotope itself. The electron stream thus reinforced will flow only in one definite direction. This is what we call a direct electric current.

One cell of this device, fractions of a cubic centimetre in size, produces an electric current of several millionths of an ampere with a tension of tenths of a volt. By connecting several thousands of such cells in parallel (in order to increase the current) it is possible to obtain a current of hundreds of milliamperes, and by connecting these sets of cells in series (in order to increase the voltage) one obtains a battery rated at several volts, which is quite sufficient to feed portable radio equipment, telephones, etc.

Since the half-life of strontium-90 is 24 years, such a nu-

clear battery can operate without recharging for 10-15 years! High-voltage (up to 150 thousand-volts) nuclear batteries are designed along different lines. True, such batteries yield a negligibly small electric current (10^{-10} to 10^{-12}A). Here, the source of fast electrons is placed on an insulator in the centre of a metal sphere or cylinder. During radioactive disintegration the radiation source emits a cloud of beta-particles (electrons) as a result of which it becomes charged positively, while the electron collector (the sphere) becomes charged negatively. A difference of potentials arises between them which produces an electric current when the electrodes are connected to a load. Such a high difference of potentials between the electron source and the sphere is due to the tremendous velocity of the electrons emitted by the beta-emitter.

If the activity of the beta-particle source is equal to one curie, such a nuclear battery will develop a power of about 200 microwatts at a working voltage of 20 kilovolts. Its service life, as well as that of the above-described design, depends on the half-life of the radioactive substance used.

Nuclear batteries may also be designed in a different way, for instance, in the form of a gas-filled tube in which radioactive radiation first ionizes the atoms of the gas and then the ions formed produce an electric current under the effect of the small difference of potentials between the two electrodes of the tube; in the form of a device in which the energy of radioactive radiation heats to a high temperature the junctions of a battery of semiconducting thermoelements producing a direct electric current. A nuclear battery may be in the form of a complex design, where a phosphor is placed in front of an electron source (a phosphor is

a substance in which bright light flashes occur under the action of electron bombardment). The light from this substance is focused on a photocell, which converts the light energy into electric energy, and so on.

Nuclear energy. A more correct and precise scientific term than the term "atomic energy" (which is more widespread) for energy released in reactions of fission of atomic nuclei of heavy elements (uranium, plutonium) or fusion of atomic nuclei of the lightest elements (hydrogen) into atomic nuclei of heavier elements (helium).

Nuclear energy levels. By analogy with the energy levels in the atom, where the chief energy carriers are electrons, the relatively stable states of a nucleus in which it possesses a strictly definite store of energy are called *nuclear energy levels.* In order to remove the nucleus from this stable state, a certain amount of energy should be added to it from outside. This may occur when it collides with a fast particle or a gamma-quantum, or when it absorbs a neutron.

For instance, in a head-on collision of a fast neutron with a nucleus of boron-11, if the neutron energy is below 2.3 MeV, the collision will be of elastic nature: the particles will simply rebound from each other, the neutron will lose part of its kinetic energy and slow down. If, however, the neutron energy exceeds 2.3 MeV, the nucleus of boron will absorb it, and, becoming excited, will after some time emit the excess energy received by it in the form of a gamma-radiation quantum.

Nuclear engine. One of the highly efficient methods for direct conversion of heat energy into kinetic energy is the rocket (jet) engine, because it is entirely devoid of any

intermediate parts such as pistons, connecting rods, and gearing systems connected to the propeller (in aircraft) or the driving wheels (in locomotives).
The chemical fuel of high calorific value burned in the combustion chamber of such an engine turns into a gas heated to an extremely high temperature and pressure, which, escaping through the nozzle with a tremendous velocity, produces a jet pushing the rocket in the opposite direction.
The velocity of rockets, all things being equal, is the higher, the greater is the exhaust velocity of the jet of heated gas leaving the nozzle. The power of the rocket engine, and consequently the weight and payload of the rocket are, in turn, the higher, the greater is the mass of the simultaneously heated and escaping gas. The exhaust velocity of the gas jet depends on the temperature and pressure which the fuel burned in the working chamber can develop.
Finally, the operation time of the engine at a given power depends on the amount of fuel which the rocket is able to carry without refuelling in flight.
In short, the velocity and power of a rocket can be increased in several ways: by raising the temperature of the heated gas, by raising the velocity of its escape from the nozzle, by increasing the mass of the heated substance or by combining all these methods, if possible.
In principle, all this can be achieved only in a nuclear engine. To effect the heating or acceleration of the substance which produces a thrust, use is made of nuclear energy obtained in a nuclear reactor.
It is hardly necessary to prove that nuclear fuel, whose

heat capacity exceeds many times over that of the best chemical fuel, opens up extremely wide opportunities in the field of space flights.

Therefore the future of space flights completely depends on the possible use of compact nuclear fuel possessing a tremendous energy and service life, which will constitute not ninety or more per cent of the total volume and weight of the rocket, as with chemical fuel, but much less, this making possible either an abrupt decrease in the total weight of the rocket or a considerable increase in its velocity and payload, all things being equal.

Nuclear energy can be used for this purpose at least in two ways: either by direct heating (by passing a working substance through a reactor, for instance, a powerful jet of hydrogen, stocks of which will naturally have to be loaded on the rocket in compressed or liquefied form), or by converting the heat produced by the reactor first into electrical energy, using it in turn for the ionization of the gas and acceleration of ionized heavy particles (see *Ion rocket*).

Nuclear engineering. A branch of modern engineering dealing with nuclear energy and utilizing it for the needs of the national economy and defence. We distinguish direct and indirect utilization of nuclear energy. The former implies reactions of fission of atomic nuclei of some elements with the aim of producing great amounts of energy, usually electrical (nuclear power industry), while the latter includes numerous uses of fission products and radiations of radioactive isotopes (in industry, science, medicine, agriculture, and engineering). Nuclear engineering also encompasses reactor building, industrial methods of

prospecting, exploration, and extraction of natural fissionable elements—uranium and thorium, the production of metallic uranium and its alloys, isotope separation, and other similar processes, design and production of all kinds of units, machines, apparatus, and instruments used in the nuclear industry and engineering.

Nuclear forces. According to the laws of physics the electric forces attracting negatively charged electrons to the positively charged atomic nucleus would make the positively charged particles collected in the nucleus—protons—scatter in opposite directions.

Contrary to these laws, however, protons within an atomic nucleus, instead of being scattered, are held together by some mysterious forces and sometimes so strongly that a tremendous energy is required to separate them or to knock even one proton out of the nucleus.

What are these forces?

These forces cannot be electrical, because even if half of the protons in the nucleus suddenly changed their positive charges to negative, they would still attract each other with a force only 40 times weaker than those which actually hold like-charged protons in the nucleus. Hence, these forces are not electrical. Maybe they are gravitational forces? But these are still less likely because the gravitational forces existing between two particles in an atomic nucleus, owing to their smallness, are 10^{37} times weaker than the forces actually holding the particles together.

Contemporary physical theory considers that the interaction between electrically charged bodies and particles is caused by photons emitted and absorbed by them, thus setting up forces of electrical attraction or repulsion.

Interaction between two nuclear particles, as shown by numerous experiments, depends not only on the distance between them, but also on the velocity of the particles relative to each other, as well as on the direction of rotation of each of these particles. Moreover, there are forces acting between three, four, and more particles simultaneously.

It should be particularly emphasized that these forces do not at all depend on the electric charges of the particles. A proton and a proton, a neutron and a neutron, a proton and a neutron—are all held close to each other with approximately the same force. The most remarkable thing, however, is that these forces act within very short ranges. At a distance equal to, say, 10^{-13} cm (1/100,000th of the radius of the atom) nuclear forces attract two protons to each other 40 times as strongly as they repel each other under the effect of two equal positive electric charges. If this distance increases only by a factor of four, the nuclear forces of attraction already become equal to the electric forces of repulsion. A 25-fold increase of the distance will result in the electrical forces of repulsion exceeding the nuclear forces of attraction already by ... a million times!

On the other hand, at distances considerably less than 0.5×10^{-13} cm the attracting effect of the nuclear forces ceases abruptly and they turn into still more powerful forces of repulsion.

Like in the case of electrical forces, interaction between nuclear particles involves the exchange of some other particles. This idea was first suggested by the Soviet physicist Academician I. Tamm.

In 1935 the Japanese physicist Yukawa, proceeding from the accumulated theoretical and experimental material, advanced the idea that the function of the quantum holding the nuclear particles together is performed by a new material particle, which he called the *meson*. He predicted also the properties of these particles, the exchange of which between a proton and a neutron gives rise to colossal forces acting over extremely short distances and only within the nucleus. These exchanged particles, to fulfil their assignment, should themselves strongly interact with protons and neutrons, regardless of their charges.

According to the general principles of quantum mechanics, forces acting over long distances, such as electromagnetic forces, can only be carried by particles which have no rest mass. Such particles, as was mentioned above, are photons. Indeed, a photon acquires a mass, i.e., a particle-like property, when moving at the velocity of light.

At the same time, forces acting over extremely short distances, according to the same laws of quantum mechanics, should be carried by particles having a mass even at rest. This mass should be the greater, the shorter is the range of action of these forces.

For forces with a range of about 10^{-13} cm the mass of such particles should be about two hundred times that of the electron.

For these particles to effect such an exchange between the different nucleons of an atomic nucleus, they should be electrically charged. When a proton and a neutron interact, the proton emits a positively charged meson, which is then absorbed by the neutron. In this process the proton loses its positive charge and becomes a neutron, whereas

the neutron acquires a positive charge and turns into a proton. The same result is naturally obtained if the neutron emits a negative meson, which is then absorbed by the proton.

The idea about the existence of a positive and a negative meson was suggested by Yukawa in accordance with the general principles of contemporary physics which state that to any charged particle there should correspond another particle of opposite charge. Such particles, which were named *μ-mesons (mu-mesons)*, were first detected in cosmic rays. Their mass was equal to 207 electron masses.

It was soon found, however, that these particles were something different from what was expected. They interacted weakly with protons and neutrons and therefore could not serve as carriers of nuclear forces. Besides, they turned out to be extremely unstable. Their mean life is only 2.2×10^{-6} sec. The disintegration of such a meson produces an electron or positron depending on the charge of the meson itself. Calculations of the energy liberated in this disintegration, and of the mass "balance" showed that at least two more particles should be produced with no charge and with a mass equal or close to zero, i.e., with a zero rest mass. These particles proved to be *neutrinos*. After a few years of considerable confusion and misunderstanding only in 1948 Powel, Occhialini, and Lattes (Englishman, Italian and Brasilian) discovered the mesons which were actually responsible for the existence of the exchange forces which hold the constituent nuclear particles together. They were named *π-mesons (pi-mesons)*. The mass of a pi-meson turned out to be 273 times that of the electron.

The conditions of the formation and existence and the

subsequent transformations of the pi-meson are of a very complicated nature. The pi-meson (which was first identified in cosmic rays), after being slowed down in the substance, disintegrates into two particles: a familiar mu-meson and a neutrino.

Then the mu-meson also slows down, following which it disintegrates, producing an electron and two neutrinos. Colliding with the nucleus, a fast pi-meson can destroy it. Unlike mu-mesons, heavy pi-mesons strongly interact with the *nucleons*. It is they that proved to be the nuclear field quanta predicted as far back as 1933, just like the photons are electromagnetic field quanta. But in order to strike an even balance it was necessary to have also an uncharged, neutral pi-meson responsible for the proton-proton and neutron-neutron interaction, when none of the nucleons turns into another. A proton, of course, cannot absorb a positive meson, since it cannot acquire a second positive charge. Consequently, not every charged meson is capable of effecting a proton-proton interaction.

Soon afterwards these missing neutral mesons were discovered in cosmic rays; the mass of these mesons exceeds the electron mass by 264 times, but they have no electric charge whatsoever.

The existence of the neutral pi-meson, among other things, explains why the action of the nuclear forces is independent of the charges of the particles making up the atomic nucleus. These mesons are also very short-lived and disintegrate into two photons. Therefore the formation and existence of the nuclear forces can be "blamed" on the three varieties of particles emitted and absorbed by nucleons: positive, negative, and neutral heavy pi-mesons.

Nuclear fuel. Natural or artificial elements whose atomic nuclei are capable of fissioning under neutron bombardment, releasing in this process a slightly greater number of neutrons (two or three) than was spent on their fission, as a result of which a branching, avalanche-like fission chain reaction may be initiated in these substances. These materials include uranium-235, plutonium-239, uranium-233, uranium-238. In the future, when a controlled *thermonuclear reaction* (fusion of atomic nuclei of light elements into those of heavier elements) is achieved, nuclear fuel will probably include all isotopes of hydrogen (protium, deuterium, and tritium), and also lithium.
Nuclear physics. This branch of contemporary physics deals with atomic nuclei, nuclear processes, and elementary particles taking part in nuclear processes and reactions. Nuclear physics forms the scientific and experimental basis of nuclear engineering and the nuclear industry.
Nuclear physics is conventionally divided into the following sections: general properties and structure of nuclei; nuclear forces; spontaneous transformations of nuclei; nuclear reactions; physics of elementary particles; neutron physics; experimental techniques of nuclear physics.
New branches of science have arisen on the basis of nuclear physics: radiochemistry, radiation chemistry, new methods of dating in geology and archaeology, and many others.
Nuclear power plant. A power plant operating on nuclear energy obtained by fissioning of heavy nuclei of uranium or plutonium which is realized in nuclear reactors of various types and purposes.
The thermal energy released in the course of reactor operation is removed from its core to a *heat-exchanger* by means

of a *heat-transfer agent* in the form of water vapour, superheated water under pressure, a gas, a low-melting metal and so on.

In the heat-exchanger the thermal energy is transferred from the heat-transfer agent to the working substance, i.e., it is converted into the kinetic energy of the vapour (gas) jet which may be directed into a steam turbine transforming the heat energy of the working substance into mechanical energy or, when necessary, into electrical energy, or may be vented out through the nozzle as in a conventional jet engine, thus setting up a reaction thrust.

Stationary nuclear power plants usually differ little from nuclear power stations. They use nuclear power reactors on slow (thermal) neutrons.

The main advantage of a nuclear power plant is very low consumption of nuclear fuel, which makes it particularly promising for various means of transportation: marine and river vessels, submarines, and aircraft. A nuclear-powered icebreaker is capable of sailing for eighteen months without refuelling, which is especially important in the Arctic, where the transportation of ordinary fuels (petroleum and coal) involves colossal difficulties, is extremely costly and requires the presence of ports and of a special fleet for carrying the tremendous amount of fast-burning fuel, including the fuel used by these vessels themselves.

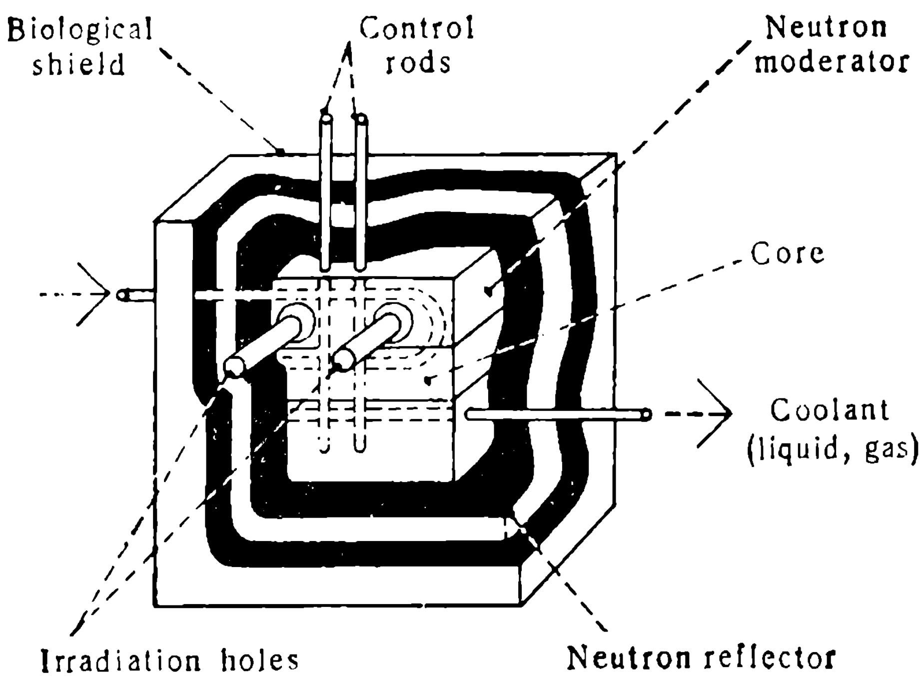
The principal disadvantage of nuclear power plants which impedes their utilization on locomotives, aircraft, automobiles, and small vessels is the bulkiness and excessive weight of the *biological shield* surrounding the nuclear reactor itself and all the elements of the unit which emit gamma-rays and neutron fluxes hazardous to people.

Nuclear power station. An electric power station which uses the energy resulting from the fission of atomic nuclei of uranium or plutonium. The first station of this kind was commissioned in the USSR on June 27, 1954, its power rating being 5,000 kW.
Since the fission of nuclear fuel results mainly in heat, at this stage of development of the nuclear power industry such a station is basically a conventional heat and power station with a nuclear reactor instead of a steam boiler. A heat-transfer agent used to remove the heat and to cool the reactor, when passing through the latter, becomes highly radioactive and presents a serious hazard to people. Therefore the reactor and all the piping in which the heat-transfer agent circulates are separated from the other, conventional part of the power station by a heat-exchanger (steam generator) where the heat-transfer agent of the closed and thoroughly isolated primary circuit transfers the heat to the heat-transfer agent (working substance) of the secondary circuit without contacting it directly.
In addition, the reactor and the rest of the primary circuit of the unit is surrounded by a *biological shield*—a concrete or water-filled wall several metres thick and capable of stopping all types of radiation.
All operations involved in the control of the reactor and the other elements of the station are automated and effected by remote control.
A number of designs of such stations have been worked out to suit the different needs of the power industry.
Nuclear reactions. Spontaneous or artificial transmutations of some atomic nuclei into others, involving rearrangement of the structure or a change in the number of nucleons in

them. Nuclear reactions may be accompanied by the following: complete disintegration of the whole atomic nucleus when hit by a particle possessing an enormous energy (velocity); absorption of another particle, usually a neutron; splitting of the nucleus into two unequal parts; emission of protons, neutrons, alpha-particles, and gamma-rays (see *Chain reaction*). Nuclear reactions include the reaction of fusion—formation of atomic nuclei of heavier elements (for instance, helium) as a result of building up of nuclei of lighter elements (hydrogen) accompanied by the release of energy eight times that liberated in the reaction of fission of atomic nuclei of heavy elements (see *Thermonuclear reaction*).

Nuclear reactor (atomic pile). The name given to a unit in which a controlled chain reaction of fission of nuclei of uranium or plutonium is carried out with the release of tremendous amounts of heat, millions of times that obtained in burning the same amount of the best fuel. The first nuclear reactor was actually a pile consisting of several hundreds of layers of big graphite bricks making up a sort of a huge graphite sphere. A comparatively small brick sphere located inside the large one and called the *reactor core* had two holes into which lumps of uranium metal or its oxides encased in aluminium cans were inserted. About 50 tons of uranium contained in the core made up its *critical mass* in which a self-sustaining fission chain reaction was initiated.
The uranium rods in the core were separated by graphite blocks, which served as a *neutron moderator*, while outward solid layers of graphite acted as a mirror reflecting

back into the core neutrons which leaked out of it and did not have time to split the nuclei of uranium-235 and escaped capture by nuclei of uranium-238.
To prevent the chain reaction from becoming too violent, cadmium rods (*safety rods*), which could be easily moved in and out of the reactor, were lowered into special channels passing through the reactor from top to bottom. The cadmium rods, which effectively absorb neutrons, prevented



them from multiplying avalanche-like in geometric progression. By withdrawing the rods gradually from the reactor it was possible to control reliably and precisely the moment of initiation of the chain reaction and the rate of its propagation so that the reaction was maintained automatically at a pre-determined level. Besides, the reactor had separate channels for introducing into the core various

substances to be irradiated with a neutron flux and for arranging the necessary measuring instruments.

In the course of operation the reactor emitted an enormous amount of very hard and hazardous radiations—neutrons and gamma-rays. Therefore it had to be surrounded with a massive concrete wall (two to three metres thick) called *biological shielding*.

Over 20 years have elapsed since the first nuclear reactor was put into operation. During this period a great number of most diverse types of reactors have been designed and built—from the smallest, the size of a football, to multi-storeyed reactors, their power ranging from fractions of a watt to hundreds of thousands of kilowatts. However, in spite of all the changes in the design and purpose of reactors, and of all the complications introduced, the basic principle of their operation still remains the same as in the first reactor.

As regards their purpose and design, nuclear reactors are now divided into the following classes: *experimental*, intended for use in scientific research; *industrial*, for producing plutonium (another kind of nuclear fuel); *power reactors*, for nuclear power stations; and many others.

Some of these types of nuclear reactor are described in more detail under the respective headings (see *Reactors*).

Nuclear weapons. Modern types of weapons whose action is based on the use of enormous energy, mainly explosive, liberated in nuclear reactions [(fission of atomic nuclei of heavy elements and fusion of nuclei of the lightest elements (hydrogen) into nuclei of heavier elements (helium)]. The nuclear weapons also include so-called combat radio-

active materials—usually radioactive products of fission of nuclei of heavy elements.

Nucleon. In order to avoid (when it is not particularly necessary) frequent repetition of the names of particles making up the nuclei of all atoms—positively charged protons and chargeless neutrons, they have been given the general name of *nucleons*, i.e., nuclear particles. The masses of these particles, however, differ by a small value: the mass of the proton is 1836 and the mass of the neutron about 1838 times that of the electron. There are grounds to believe that the proton and the neutron are identical particles, the only difference being that the proton is positively charged and the neutron is uncharged; these particles can convert into one another under certain conditions.

Nucleus, atomic. The core of the atom in which the bulk of its mass is concentrated. The nucleus consists of nucleons—protons and neutrons (with the exception of the nucleus of hydrogen which consists of just a single proton). The total number of protons and neutrons in the nucleus determines the atomic weight of the element, while the number of protons determines its atomic number in Mendeleyev's Periodic Table of Chemical Elements. Each atomic nucleus is characterized by a definite *binding energy*, which holds its component particles together.

O

Optics, electron. The branch of physics concerned with the motion of free electrons under the influence of electric and

magnetic fields. The term *electron optics* is derived from the fact that the laws governing electron paths in such fields are formally identical with those governing light rays in media of varying refractive index.

Electron optics finds application in the formation of electron beams as in cathode-ray tubes and television camera tubes; in the deflection of such beams by electric and magnetic fields; and in the formation of electron images, as in electron microscopes and image tubes.

P

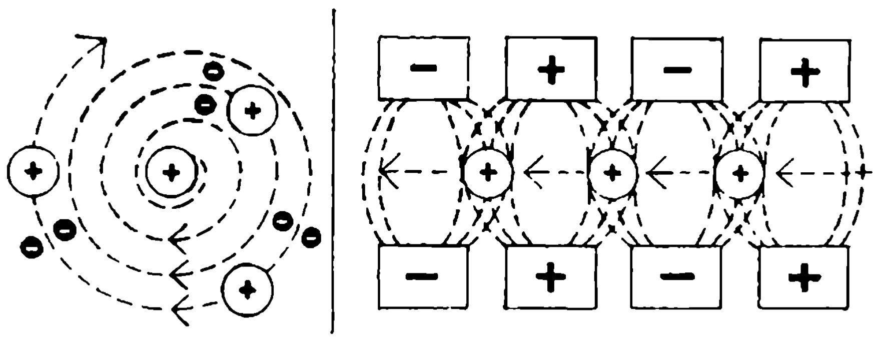
Particle accelerators. In the early investigations of the atom and its nucleus, the scientists could be content with the energy of alpha-particles ejected in the natural disintegration of radioactive substances. But soon this became insufficient. Therefore special, very intricate units had to be built for artificial acceleration of atomic particles. How are they accelerated?

We know that once a charged particle gets into an electric field, its motion is gradually accelerated, and finding itself in a magnetic field it begins to "wind" around the imaginary lines of force of this field.

This gave the scientists the idea to use magnetic fields for building a heavy "atomic artillery"—*charged-particle accelerators*. In an electric field the particles are accelerated in a straight line. This type of accelerator is called *linear*. In a magnetic field the particles are given a spiral

motion as well. Such machines are called *circular-orbit accelerators.*

A *linear accelerator* is a long, straight tube, thoroughly evacuated. Inside the tube a great number of electrodes—metal *drift tubes* carefully insulated from the main tube—are arranged one after another. The length of the electrodes gradually increases towards the output end of the accelera-



tor. A comparatively low alternating electric voltage is fed to each two neighbouring electrodes from a special high-frequency generator.

When the first drift tube is charged, say, positively, at a certain moment, the following tube will be charged negatively. The next tube is charged positively again, and the one following it is charged negatively, and this pattern is repeated up to the end of the accelerator. The voltage on the drift tubes is changed continuously so that the positive and negative charges "chase" one another along the accelerator electrodes.

As soon as a portion of previously accelerated charged particles, say electrons, are "injected" into the accelerator, they begin to accelerate to a still higher velocity under the influence of the neighbouring positively charged elec-

trode, and rush further through this electrode. At this moment the charges on the tubes reverse. The electrode, which a moment ago attracted electrons, becomes negative and begins to "push forward" the electrons that have passed through it. The approaching beam of electrons is now attracted by the next drift tube, which has now become positively charged only to change its charge to a negative one after the cloudlet of electrons has passed through it, and to push this portion of electrons further on.

Strictly speaking, the acceleration of an electron beam takes place only in the gap between the drift tubes. Inside them the particles are protected from the action of the electric field and move at a constant velocity, "drifting" through them. As the electrons move forward their velocity gradually increases. The accelerating tubes are made correspondingly longer.

Having passed the entire length of the accelerator, the portion of electrons is accelerated to a velocity close to that of light and acquires an energy measured in hundreds of millions or even thousands of millions of electron-volts. The portion of accelerated electrons is directed through an air-tight window placed at the end of the tube to special units for irradiating substances under investigation.

Circular accelerators. The same can be achieved by a somewhat different method. Imagine that our long tube is bent into a spiral. To avoid the crowding of the accelerating electrodes, we can remove them all, leaving only two electrodes made in the form of halves of a huge ring placed over a spiral. The whole combination is arranged between the poles of a huge magnet. Then, instead of moving in a straight line, the charged particles will move along

the spiral under the action of the vertical magnetic field. Thus we can simply leave, in place of the bent tube, an evacuated flat circular chamber without any internal partitions. Now we can feed high-frequency alternating electric voltage to the two semicircular electrodes, called *dees*. When one of them carries a positive electric charge, it draws the electrons inside, and the other, which is charged negatively, pushes them forward.

The portion of charged particles to be accelerated is injected in the centre of the imaginary spiral. At first they gather speed rather rapidly, but then this process slows down and then ceases altogether, since the closer the particle velocity approaches that of light, the heavier the particles become and they gradually begin to lag behind the electric voltage on the dees which changes its sign. The acceleration limit is somewhere between 20 and 30 MeV. Such units are called *cyclotrons*.

In order to overcome the obstacle to the further acceleration of particles, the frequency of the electric voltage which is fed alternately to the accelerating electrodes, is made variable—as the particles become accelerated the frequency drops off so as not to outrace the particles. On these units, which are called *synchrocyclotrons*, particles, for instance, protons, can be accelerated to energies of 600 to 800 MeV.

As the energy of the missiles of the atomic "artillery" increased, new and finer details in the structure of atomic nuclei and their component nuclear particles were revealed, and the mysteries of birth of new particles, whose number had already exceeded thirty, were unravelled.

Therefore scientists began to build still more powerful accelerators—*synchrotrons* and *proton synchrotrons*, in which

particles move not along a spiral, but along a circular path in an annular chamber resembling a gigantic doughnut, while acceleration is effected only at one or several points in the path of the particles.

At first 2.9 and 6.2-GeV units were built in the USA, then a 10-GeV unit in Dubna (USSR), and finally a 25-GeV machine in Bern (Switzerland) and a 33-GeV one in Brookhaven (USA). In the USSR a virtually gigantic, world's most powerful accelerator for 60-70 GeV is under construction and even more powerful units are being designed.

Photoemulsion method of particle recording. Shortly after X-rays and the phenomenon of radioactivity were discovered it became generally known that these radiations, invisible to the naked eye, affect a photographic plate many times stronger than the brightest rays of visible light.

The light-sensitive emulsion of a photographic plate or film usually consists of tiny grains of silver bromide suspended in a thin layer of transparent gelatine mass. The grains of the chemical compound of bromine and silver are entirely transparent. The outermost electron shell of the bromine atom contains seven electrons, hence it lacks only one electron to complete the octet (eight electrons). The silver atom, on the contrary, has only one electron in its outermost shell, and therefore the bond between these two atoms is very strong.

When the silver bromide grains of the photoemulsion are acted on by light quanta, the latter knock these bonding electrons out of the crystal of silver bromide, as a result of which the atoms of pure silver become free and remain opaque after developing, and their clusters appear to be black.

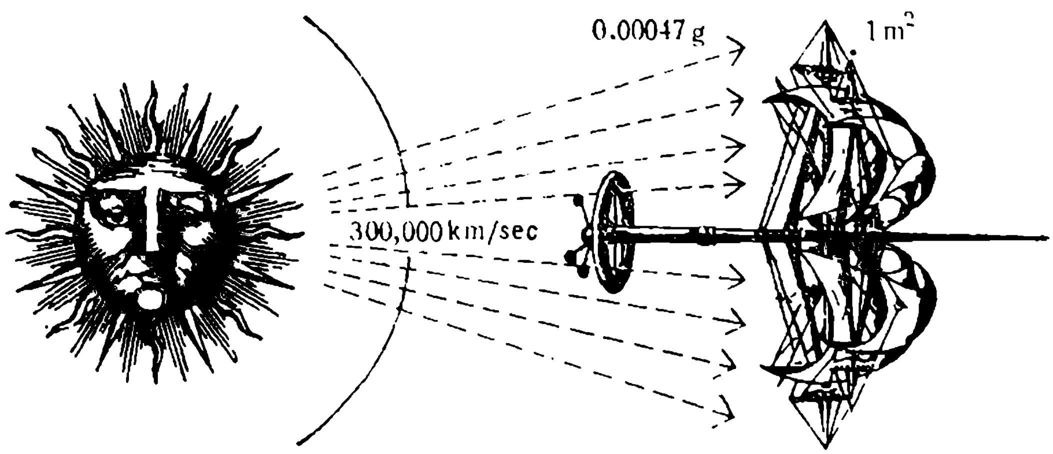
Apart from light quanta, electrons are knocked out of silver bromide by any electrically charged particles possessing an energy sufficient to ionize or even split the atomic nuclei of the silver. Passing through the photoemulsion, they leave behind them traces of ionized silver molecules which, after the plate is developed, are observed under a microscope as a chain of dots of dark silver against the background of the transparent emulsion.
Since even alpha-particles emitted by radioactive substances leave a track about 50 μ (0.05 mm) long and the emulsion of ordinary plates is only 20 μ thick, the tracks of particles moving perpendicularly to the plates extend beyond the emulsion layer, to say nothing of particles flying with a considerably higher velocity. The Soviet physicist Mysovsky was the first to suggest the production of plates with an emulsion layer of 400 to 600 μ. When the range of the particle proves still longer, use is made of multi-layer emulsion stacks.
Photon. A quantum of energy of visible and invisible light, X-rays and gamma-rays which possesses both wave-like and particle-like properties. The photon has no rest mass and can move only with the velocity of light, i.e., 300,000 km/sec. The photon has no electric charge, it is electrically neutral. Since electromagnetic waves of any frequency can be emitted only in strictly definite portions—*quanta*, the energy of the photon depends on the frequency of radiation and is equal to

$$E = h\nu$$

where E is the energy of the photon, h the Planck constant, and ν radiation frequency.

Under certain conditions a photon possessing a sufficiently high energy may form a pair of particles, an electron-positron pair.

Photon rocket. It is well known that the fission of atomic nuclei of uranium or plutonium is accompanied by the liberation of an enormous amount of energy—about 22.9 million kWh per 1 kg of fissionable material. But even this colossal amount of energy comprises only 0.1% of the energy latent in the substance (more precisely, the equivalent mass of the substance) which is obtained according



to Einstein's famous mass-energy equation $E=mc^2$. Even a thermonuclear reaction of fusion of light atoms into heavier nuclei releases only about 1% of the latent energy! Only one process is known to occur in nature in the course of which the entire mass of the participating substance turns into radiation, i.e. photons, which have no rest mass, but which move with the velocity of light—300,000 km/sec. This is *pair annihilation*: mutual destruction of two particles having opposite physical properties—an ordinary particle and a so-called "antiparticle", for instance, an electron

and a positron, a proton and an antiproton (see *Elementary particles*). Such a reaction liberates the entire energy latent in the substance or, according to the above Einstein equation, 25 thousand millions of kWh per each kilogram of the substance!

A few decades ago P. Lebedev proved that light, which possesses a mass in addition to energy, exerts a small but measurable pressure. Therefore a powerful flux of photons created by a fantastically huge lamp emitting a sea of light in some direction or other should impart continuous acceleration to this mass. Such a rocket engine, which is so far in the sphere of science fiction, is conceived as a nuclear plant of tremendous power, continuously producing particles and antiparticles, for instance, protons and antiprotons. These particles, colliding in a special chamber, annihilate each other, and the photons produced and collected with the aid of a big mirror are ejected from the tail-end of the rocket in the required direction. The reaction thrust is built up by the light flux.

Theoretically, this type of engine is energetically the most perfect, efficient and economical, because in the course of pair annihilation practically 100% of the energy latent in the substance is transformed into light, and the photons themselves move with the velocity of light, the maximum possible velocity in nature.

In the future, however, the scientists will face extremely difficult tasks. The most important of them are as follows. In our world of ordinary elementary particles it is difficult, but still possible, to obtain antiparticles. But it is almost a hopeless undertaking to try and keep them from entering into a nuclear reaction with the surrounding counterparts.

Moreover, they should be carried to the combustion chamber placed in the focus of the rocket mirror.
For the thrust of such an engine to be sufficient, quite appreciable amounts of matter should transform into light. The process of annihilation and transformation of matter into light will take place at an incredibly high temperature which will vaporize any, most fantastically heat-resistant material of the mirror. The light flash will be incomparably brighter and more powerful than in the explosion of a multimegaton hydrogen bomb.
We cannot, however, predict what science and engineering will achieve even in a few decades. In the distant, or may be not so distant future, science will undoubtedly solve this breath-taking task as well. Therefore, despite the seemingly hopeless prospects at the moment, the scientists give considerable attention to the idea of creating a photon rocket, which is still a very abstract idea, rather like a dream.
Why is the development of the photon rocket, or even the dream of it, so attractive?
The cosmic distances of tens and hundreds of light years which separate us from the nearest stellar worlds, to say nothing of the distances to other galaxies, prevent man from realizing his long-cherished hope of shaking off the fetters of time and space. Even moving with the velocity of light, a rocket would need four and a half years to reach the nearest star! And only an engine enabling a rocket to move with a near-light velocity can help man to materialize the dream of reaching the worlds outside the solar system.
Pi-meson (π-meson, pion). An unstable elementary particle with a mass 273 times that of the electron. There exist

three types of such particles: the positive and negative pi-mesons possessing electric charges equal in absolute value to the electric charge of the electron, and the neutral pi-meson. The mass of charged pi-mesons is 273 times that of the electron, and the mass of the neutral pi-meson is slightly less, 264 electron masses. The pi-meson is produced on nucleons or nuclei under bombardment with nucleons and high-energy gamma-rays. The mean life of a charged pi-meson is about 2.5×10^{-8} sec. In most cases a pi-meson disintegrates into a mu-meson and a neutrino. In contrast to mu-mesons, pi-mesons actively interact with atomic nuclei. Among other things, they are responsible for the existence of *nuclear forces*. Exchanging pi-mesons, the nucleons are held together in spite of the existence of colossal forces of repulsion between positively charged protons striving to "explode" the nucleus from within.

Plasma — the fourth physical state of matter. We all know that a substance can only exist in three physical states: solid, liquid or gaseous. One classical example is water, which can exist as ice, liquid or vapour. In fact, however, in the Universe as a whole very few substances are actually in one of these states, which are usually taken for granted and considered universal. They actually constitute what the chemists call trace amounts. All the remaining matter of the Universe is in the so-called *plasmatic state*. What is this?

It is generally known that as a solid body is heated the thermal motion of its atoms becomes more and more energetic until the bonds determining the structure of the substance begin to weaken and then rupture one after another.

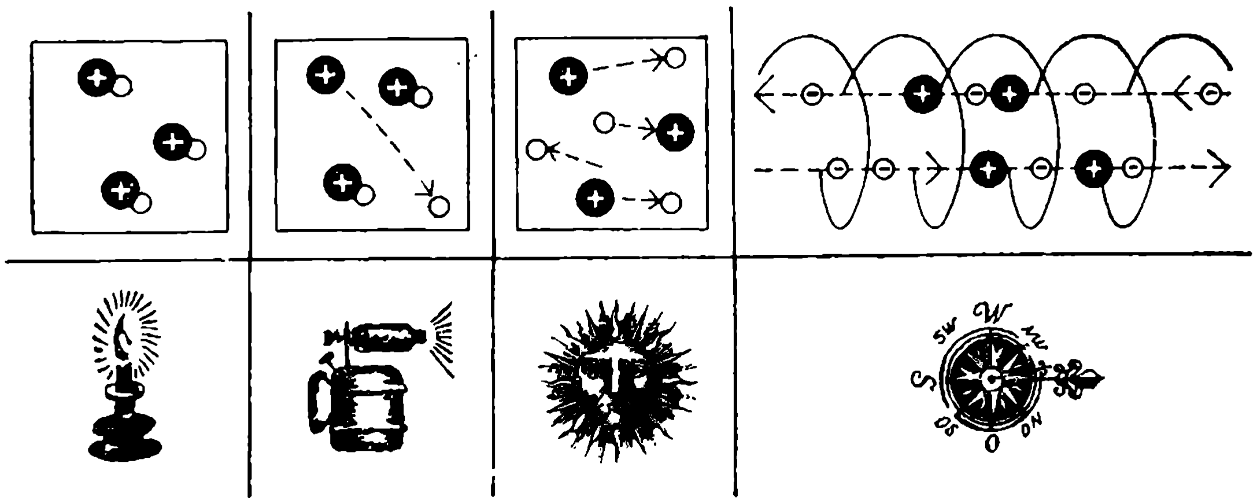
The first to break up is the crystal lattice: the solid melts and turns into a liquid. Then the bonds between the molecules are weakened, and the body becomes a gas, i.e., it evaporates. Above 2000 °C water cannot exist as a liquid, no matter what the pressure. Thus, no chemical reactions are possible in the aqueous medium any longer. At four to five thousand degrees all bonds inside the molecules are broken, and the substance is ultimately decomposed into atoms of the constituent elements. Therefore all ordinary chemical reactions cease to proceed.

What will happen then if we heat a vessel containing a gas?

As the temperature rises, the motion of the gas atoms becomes more and more vigorous and they collide with each other more and more often, and consequently, more and more energetically. As a result of these collisions, the outermost electrons begin to tear away, since their bond with the nucleus is the weakest. Inside the gas there appears a "second" gas consisting of these electrons, whose number grows continuously as the atomic nuclei are stripped. Then the electrons "hidden" in the innermost and strongest orbits begin to detach. At the same time collisions between ions, that are devoid of all or part of their electron protection, become more frequent.

A gas in which the substance has been separated, under the effect of extremely high temperatures, into free electrons, entirely stripped atomic nuclei, and atoms, which by sheer luck still retain a fraction of their electrons—all rushing about at break-neck speed and colliding between themselves and with the walls of the vessel—was given the name of *plasma*. The "ideal" plasma with completely

separated atomic particles corresponds to a temperature of tens of millions of degrees Celsius. Any extremely hot substance is in the plasmatic state.
But plasma is not only a substance heated to a superhigh temperature. It is an entirely different physical state with a number of important and even unusual properties.
For instance, the plasmatic state of a gaseous substance may arise also at moderate or even relatively low temperatures, depending on the composition, structure and degree



of rarefaction of the gas. The flame of a candle, the glow of fluorescent lights, an electric arc, an electric discharge, a flame jet escaping from the nozzle of a jet engine or a rocket, the blinding streak left by a lightning—these are but a few of the phenomena where man deals, directly or indirectly, with the fourth, plasmatic state of matter and sometimes even utilizes it for practical purposes.
Most people and even some scientists make no distinction between some types of plasma and gas. Indeed, one may

often hear of the hot atmosphere of the Sun and stars, currents of hot gases, and so on.

Of course, plasma is closely similar to gas in some of its properties. It is rarefied and fluid. However, its structure, at the atomic and molecular level, is quite different, and this accounts for a vast diversity of its properties and behaviour, which sharply distinguish plasma from the other states of matter. On the whole, plasma is neutral, since it contains equal numbers of negatively and positively charged particles. But interaction of these charges imparts to plasma an amazing diversity of properties different from any properties of gases.

Under certain conditions plasma may conduct an electric current better than copper, flow as a viscous fluid, react with other substances as a strong chemical solution. What is more, plasma is easily controlled by electric and magnetic fields.

Within an incredibly short period plasma physics has become one of the leading branches of science, mainly due to the investigations of the thermonuclear reaction, which so far has only been obtained in an instantaneous flash of a plasma heated to several hundreds of millions of degrees Celsius in a hydrogen bomb explosion (see *Thermonuclear reaction*).

Plutonium, Pu. A chemical element with an atomic number of 94 and an atomic weight of 239 first obtained by man in the course of a controlled chain reaction of fission of uranium nuclei.

As is well known, utilization of nuclear energy by man began with uranium-235, which was and still is the most important nuclear fuel. Having even a mountain of natural

uranium one could not use a single drop of its latent energy if it did not contain the fissionable isotope uranium-235. This isotope is fissioned equally well by neutrons of any energy. Natural metal, however, contains very little of it—only 0.7%, the remaining 99.3% being uranium-238, which can be fissioned only by fast neutrons. But uranium-238 extremely effectively absorbs *intermediate neutrons* of energy from 1 to 10 eV. This is where miracles begin. If the fast neutrons ejected in the fission of uranium-235 are slowed down to this energy with the aid of a moderator—graphite, heavy or ordinary water or other substances, the atomic nucleus of uranium-238, capturing such a slow neutron, becomes strongly excited and, disintegrating, transforms ultimately into plutonium with a half-life of 24.40 years.

The most remarkable thing is that it becomes a "double" of uranium-235: it is also fissioned by both fast and slow neutrons. It becomes possible during the burning of uranium-235 to convert a certain fraction of practically non-fissioning uranium-238 into fissionable plutonium-239. In this manner, by gradually burning out uranium-235 (0.7%) and plutonium-239 obtained indirectly (of course, less than 0.7%) in a nuclear reactor, it is possible, all in the day's work, to convert a considerable portion of natural uranium-238 into nuclear fuel as well.

Pure plutonium-239 is a strong poison, and it readily ignites in air. On disintegrating it emits alpha-particles of about 5 MeV energy.

Ingress of plutonium into a human or animal organism is particularly hazardous because it cannot be removed by natural processes. Prolonged internal irradiation with

gamma-rays causes acute radiation sickness or even death.

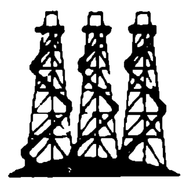
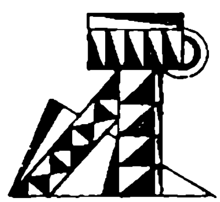
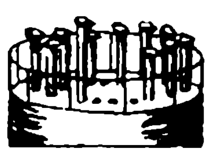
Pneumatic suit. A special suit for work in an atmosphere contaminated with radioactive substances—dust, gases, aerosols. The protective properties of the suit are due to the fact that air under a pressure slightly higher than atmospheric is continuously fed into it; this precludes the ingress of radioactive particles into the pneumatic suit. The suit enables a man to move freely and work for a certain period of time in a contaminated room, it can easily be washed to remove the radioactive particles clinging to it, and it is provided with forced (as in diving equipment) or self-contained (gas cylinders) air supply.

Positron (positive electron). An elementary particle discovered in 1932 which is identical to the electron in mass, magnitude of charge, etc., but has the opposite, positive charge; therefore it is the *antiparticle* of the electron—the first in the series of the discovered antiparticles. A positron results from the annihilation of two or three quanta of gamma-radiation or from the beta decay of nuclei or unstable nuclear particles. When a positron encounters an electron, they annihilate each other. This reaction results in two or three quanta of gamma-radiation (photons).

Power output of a nuclear reactor. The intensity with which energy is liberated in a nuclear reactor depends on the number of fissions of atomic nuclei of uranium or plutonium per second.

Theoretically, the power of a reactor may have any value; in practice, however, it is limited by the comparatively low temperature that the structural materials of the reactor can withstand, the ability of the heat-transfer agent to absorb, transfer and give off heat, the permissible speed

of its pumping, the properties of the neutron moderator, and by other factors.

	Fuel	World reserves, tons	Power, kWh
Petroleum Natural gas		$0.12 \cdot 10^{12}$ $0.06 \cdot 10^{12}$	$0.97 \cdot 10^{15}$ $0.49 \cdot 10^{15}$
Coal		$10.7 \cdot 10^{12}$	$86.0 \cdot 10^{15}$
Uranium Thorium		$6.5 \cdot 10^{12}$	$527 \cdot 10^{15}$
Annual solar energy supply to Earth			$1{,}500 \cdot 10^{15}$
	Annual world power consumption		$3 \cdot 10^{12}$

The amount of heat released in a nuclear reactor per second under nominal operating conditions is called the heat output of the reactor.

When a nuclear reactor is used in power plants, for instance, in nuclear power stations or on surface vessels and submarines, the heat output of the reactor is usually three or four times that of the electric power of the whole installation (the efficiency being from 20 to 35%). Thus, with the electric output rating of the world's first Soviet nuclear electric power station in Obninsk equal to 5,000 kW, the heat output of its nuclear reactor was 300,000 kW.

Power sources on Earth. The power sources on Earth consist basically of two types: fuels (coal, petroleum, etc.) and non-fuels (falling water, wind, etc.). Besides, the power sources are also divided conventionally into restorable and non-restorable. Data on power sources are given on pp. 187-189.

Protium. The atom of light hydrogen whose nucleus consists of a single proton. This name is more convenient whenever it has to be used along with *deuterium* (atom of

Non-restorable Power Sources (Fuel)

	Reference fuel, thous. mil.tons	mil.mil. kWh
Coal	10,660	86,250
Petroleum	120	970
Natural gas	60	490
Peat	560	4,550
Vegetable fuel	600	4,800
Uranium and thorium	65,000	527,000

Continuously Restored and Practically Eternal Power Sources

	mil.mil. kWh
Solar radiation	1,500,000
Sea tides and waves	70,000
Wind power	17,360
Earth heat	289
River power	33

heavy hydrogen) or *tritium* (atom of superheavy hydrogen). Hence, the proton is the atomic nucleus of *protium*, *deuteron*—of deuterium, *triton*—of tritium.

Proton. One of the few stable elementary particles which enters, along with the neutron, into the composition of all atomic nuclei of chemical elements, with the exception of the lightest isotope of hydrogen ($_1H^1$) whose nucleus consists of a single proton.

As we know, hydrogen occupies the first place in Mendeleyev's Periodic Table of Chemical Elements, and hence the name of this element *protium*—from the Greek word *protos* meaning first.

Although the elementary electric charge carried by the proton is equal to that of the electron (but opposite in sign), the mass of the proton is 1836 times that of the electron. When there is no special need to indicate the charge of either of the nuclear particles, the proton, like the neutron, has a more general name—the nucleon. This is all

the more correct because it is now an established fact that the proton and the neutron are merely different physical states of one and the same elementary particle. When an atomic nucleus absorbs energy from outside and disintegrates, the proton inside the nucleus may turn into a neutron. This process is accompanied by the production of one more charged particle—a *positron*, whose mass is precisely equal to that of the electron, but which carries the opposite (positive) electric charge, and of one more uncharged (neutral) particle—a *neutrino*, which has a zero rest mass and moves exclusively with the velocity of light. When a neutron turns into a proton, the atomic nucleus ejects an electron and again a neutrino in place of a positron.

Proton radioactivity. Until recently scientists knew the following basic types of radioactive disintegration of atomic nuclei. Three of them—emission of alpha-particles (atomic nuclei of helium), beta-particles (electrons), and gamma-rays—have been known since the time of Marie and Pierre Curie. Another type of disintegration—*spontaneous fission* of atomic nuclei of uranium with the emission of neutrons, electrons, and gamma-quanta—was discovered by Soviet scientists Flerov and Petrzhak in 1940 and, finally, still another type—emission of neutrons by the decay products of uranium nuclei (delayed neutrons)—was discovered a short time after this fission had already occurred.

At one time, proceeding from the results of theoretical research, some scientists predicted the existence of still one more type of disintegration in which the nucleus of an excited atom (i.e., the nucleus that has absorbed a certain amount of energy from outside) emits a proton, a positively charged elementary particle. This, so-called *proton radio-*

activity was discovered by Soviet scientists in 1962. There are some other types of radioactivity: *K-capture*, *isomeric transitions*, *positron disintegrations*, *delayed protons*, etc.

Proton synchrotron. A type of particle accelerator (see *Particle accelerators*). This type of accelerator of heavy charged particles, in contrast to the *cyclotron* and *synchrocyclotron*, uses a changing controlling magnetic field, which periodically increases and decreases to a certain initial value. This enables the particle to move not along a spiral, as in the case of the cyclotron and synchrocyclotron, but in a circular orbit of constant radius. To each increase in the intensity of the controlling magnetic field there corresponds a definite increase in the frequency of the accelerating voltage, and this makes it possible to "whip" more and more frequently the particle, which circles with an ever-increasing velocity in one and the same orbit. Under these conditions of motion the magnetic system can be given the shape of a ring assembled of separate electromagnets. However, in order to achieve high energies of the accelerated particles a very large electromagnetic system is required. The magnet of the proton synchrotron in Dubna, which accelerates particles to an energy of 10,000,000,000 eV (10 GeV), weighs about 35 thousand tons.

A further increase of energy in this type of accelerator would require the use of still more powerful magnetic systems. Therefore more effective principles of accelerator operation are being sought and elaborated. In particular, many difficulties have been surmounted by using the principle of strong focusing suggested by the Soviet scientist Veksler. It consists essentially in increasing the magnetic "compression" of the beam of accelerated particles from all

sides with the aid of a controlling magnetic field of a specially selected shape. As distinct from the old accelerators with weak focusing, where the particles were focused by a magnetic system in the vertical and horizontal directions simultaneously, accelerators with strong focusing use "division of labour". The magnets focus the particles alternately in the vertical and horizontal directions. This permits of more accurate focusing of the particle flux and of sharp reduction in the size of the chamber and in the weight of the magnet. Use is made of magnets in which the field is sharply increased with radius. This design considerably reduces the deflection of the particles in their motion in the vacuum and enables the size of the vacuum chamber and the magnetic system to be reduced still further.
The strong-focusing principle is used in all the largest accelerators built in recent years. It is applied in the world's largest accelerator for 60-70 MeV built in Serpukhov (USSR).

Q

Quanta. Quantum theory. Although the behaviour of light rays, X-rays, and gamma-rays under normal conditions was for a long time considered a convincing proof of their wavelike properties, a number of phenomena were also known which were in contradiction with the wave theory. They could readily be explained only on the assumption that very short electromagnetic waves, at least in their interaction with matter, possess the properties of discrete particles,

i.e., bodies having a definite, finite size, but which can exist and move only with the velocity of light.

In 1901 the prominent German physicist Max Planck advanced a theory according to which in the process of physical transformations and interactions of atoms of matter energy is radiated and absorbed in discrete amounts, or "packages", instead of continuously. Such a portion of energy later received the name of the *quantum*.

Consequently the absorption of light rays, X-rays, and gamma-rays by various substances, and also the emission of light by excited atoms, say those of a substance heated to a high temperature, takes place in strictly definite discrete portions—quanta. According to Planck, the energy of a quantum is obtained by the equation*

$$E = h\nu$$

where E is the energy, ergs; ν the frequency of the radiation, 1/sec; h a proportionality constant equal to 6.65×10^{-34} joule · sec (now called *Planck's constant*).

From this rather simple expression it follows that the higher the frequency of electromagnetic radiation, the greater the energy carried by a single quantum of radiation.

However, quanta of energy can only be absorbed and emitted if they reach a strictly definite value characteristic of a given physical process.

The *photoelectric effect* is a physical process in which light quanta falling on a metal surface free the electrons from

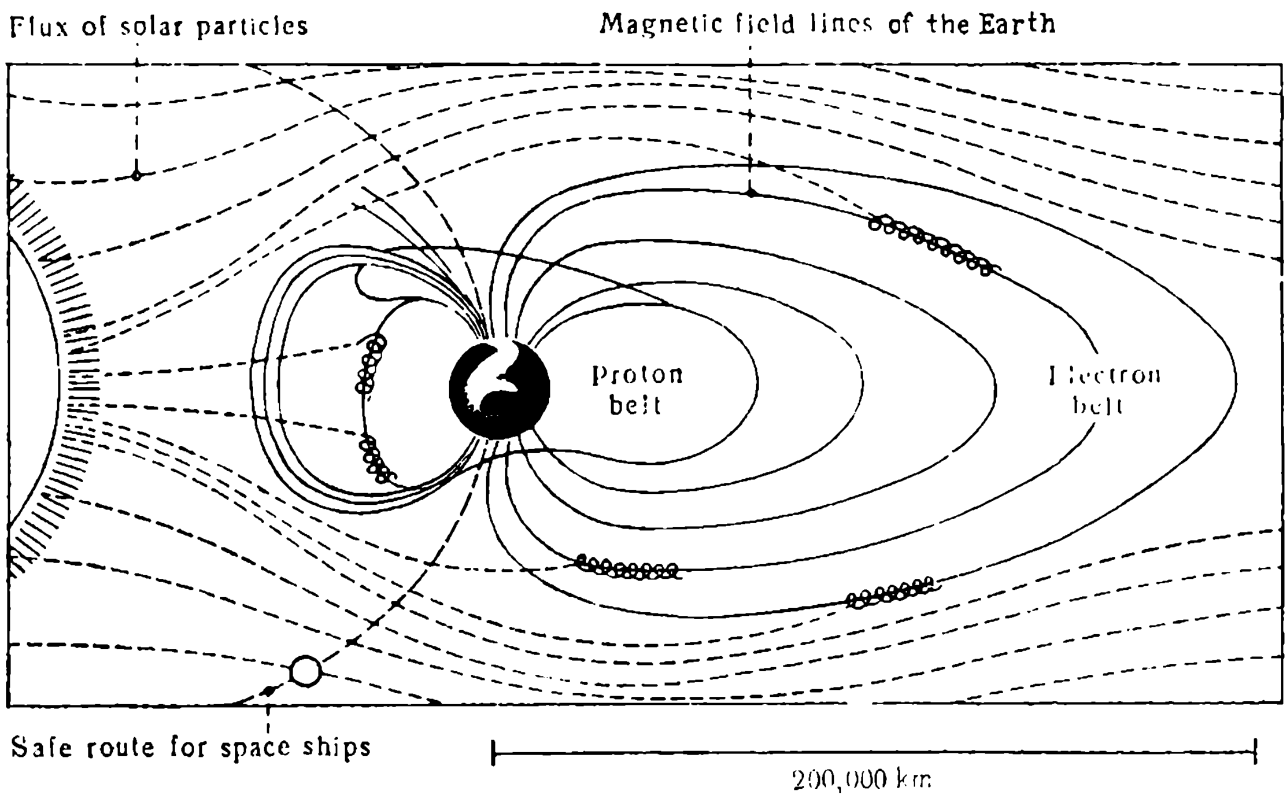
* The frequency is often represented by the letter f in this equation —*Ed.*

the metal if the quantum energy is sufficient. Such portions of light were named *photons* by Einstein, who thus emphasized the corpuscular properties of light.

R

Radiation belts of the Earth (Van Allen-Vernov belts). After the discovery of *cosmic rays*, fluxes of particles entering the Earth's magnetic field from space, the progress in this new and extremely important branch of physics almost completely depended on the altitude to which scientists could raise intricate devices and counters above the ground. Use was successfully made of high-mountain observatories, laboratories, balloons, probes, stratostats. However, even the maximal height achieved (20 to 80 km) was not sufficient to carry the devices beyond the comparatively dense layers of the atmosphere, which made it very difficult to isolate from the recorded flux of a great diversity of particles their most important component—*primary cosmic rays*.
And it is natural that the payload of rockets which first escaped into outer space mainly included various instruments for the study of charged particles. The very first signals from the devices transmitted automatically to Earth caused surprise among scientists. At certain altitudes space laboratories found themselves in regions densely saturated with charged particles of very high energies widely differing from the previously observed cosmic rays, both primary

and secondary. This phenomenon was revealed during the flights of Soviet and American satellites, and the scientists were puzzled for some time by the sharp divergency in the data obtained—a rare case in exact sciences. Soon afterwards, however, this riddle was explained. A Soviet scientist, Vernov, and almost simultaneously an American physicist,



Van Allen, established that the Earth is surrounded in the equatorial plane by two (according to more recent information even three) comparatively distinct belts (magnetospheres), resembling gigantic doughnuts, densely populated by charged particles with different charges, energies and masses. The particle concentration in each belt varies from boundary to boundary, the space on both sides of the

poles being practically free of charged particles. After the data obtained in the first rocket launchings and satellite flights had been processed, it became clear that the charged particles had been captured by the magnetic field of the Earth.

It is well known that any charged particles, once they get into a magnetic field, begin to "wind" around the lines of force, simultaneously moving along them. The size of the turns of the spiral obtained depends on the initial velocity of the particles, their mass and charge, and on the intensity of the Earth's magnetic field in that region of circumterrestrial space which they entered and where they changed the direction of their flight. The Earth's magnetic field is non-uniform. It is denser near the poles. Therefore a charged particle which began moving on the spiral along the magnetic line "straddled" by it from a near-equator region, as it approaches either pole, meets with an ever-increasing resistance until it stops, and then it goes back to the Equator and further towards the opposite pole, from which it starts moving in the reverse direction. The particle finds itself in what may be called a gigantic magnetic trap of the planet.

The first belt begins at an altitude of about 500 km above the Western hemisphere and 1,500 km above the Eastern hemisphere of the Earth. The highest concentration of particles in this belt—its "nucleus"—is at an altitude of two or three thousand kilometres. The upper boundary of this belt reaches three to four thousand kilometres above the surface of the Earth. The second particle belt extends from 10-11 to 40-60 thousand kilometres with a maximum concentration of particles at the altitude of 20

thousand kilometres. The outer belt begins at an altitude of 60 to 75 thousand kilometres.
The indicated belt boundaries have so far been determined only approximately and they evidently change periodically within certain limits. It is the regularities of these changes that the scientists are trying to establish by systematically launching numerous satellites bearing instruments for detecting energetic particles at various altitudes.
These belts differ from each other in that the first one, the closest to the Earth, consists of positively charged protons possessing a very high energy, of the order of 100 MeV. Only the densest part of the Earth's magnetic field could capture and retain them. The second belt consists mainly of electrons with an energy of "only" 30-100 keV. The third belt, where the Earth's magnetic field is the weakest, contains particles with an energy of 200 eV and over. Considering that ordinary X-rays, which are used for short periods for medical purposes, possess an energy of 30 to 50 keV, while powerful units for irradiating huge ingots and lumps of metal are rated at 200 keV to 2 MeV, it is easy to see what a great hazard these belts (particularly the first and the second) present to the people and animals and to future astronauts that will travel to other planets. That is why the scientists are striving so persevereutly and painstakingly to determine the precise location and shape of these belts, and the particle distribution in them. So far only one thing is clear. Regions close to the magnetic poles of the Earth and free of high-energy particles will serve as corridors leading manned spaceships onto the routes to other worlds.
It would be natural to pose the question: where do these particles come from?

They are mainly ejected by our Sun from its depths. It has been established that the Earth, despite its great distance from the Sun, is just in the outermost zone of its atmosphere. This is confirmed, for one thing, by the fact that each time solar activity increases, and so do the number and energy of the particles emitted by the Sun, the number of electrons in the second radiation belt also increases and the belt is pressed down to the Earth as if under the pressure of this particle "wind". Also caught in the magnetic trap of the Earth are cosmic particles whose energy was insufficient to get through it, and also particles formed as a result of collisions of high-energy primary cosmic rays with atoms of the uppermost and extremely rarefied layers of the atmosphere, which actually extends much farther than was believed until recently, almost as far as 150 km from the surface of the Earth.

We do not even realize what reliable shields for men and in general for all living beings on Earth are the transparent and almost intangible atmosphere and the entirely invisible and impalpable magnetic field of our planet. Living matter with its supreme form—man—has completely adapted itself, during the hundreds of millions of years of evolution, to the comparatively small part of radiations that penetrates through the double natural "armour" of the Earth, and it is hard to imagine what forms life on the planet would have taken if it had not been completely protected from all types of cosmic radiation. Men flying into outer space are automatically deprived of their life-saving shield—the atmosphere and magnetic field —and this subjects them to the effect of all types of radiation at once.

The radiation belts of the Earth are especially dangerous

because of the high concentration and energy of the electrons trapped in them. Hitting the walls and any metal objects of a spaceship, all electrons of energies above 10 keV give rise to so-called *bremsstrahlung*—X-rays which, like the particles, ionize the substance of the cells of the human body and cause its destruction. It would be most simple to protect astronauts from this radiation by increasing the thickness of the walls of the crew's module, by lining them, for instance, with a thick layer of lead. But this would make the spaceship prohibitively heavy. According to the foreign press, scientists are attempting to solve this problem by setting up an artificial magnetic or electric field all around the spaceship (by analogy with the Earth) that would be strong enough to deflect all the particles encountered. At the same time scientists are searching for other ways of protection, for instance, drugs, which would eliminate or sharply reduce the harmful effects of radiation on the cells of the organism. Some scientists believe that if astronauts are plunged into hypnotic sleep or even are cooled to the state of anabiosis, in which all the vital functions of the body are greatly retarded and consequently oxygen consumption is sharply decreased, it will reduce to the same extent the harm inflicted on the cells by ionizing radiation.

Radiation chemistry. A new branch of the chemical science dealing with the effect of radiations on the chemical and physical properties of various substances. In many cases the effect of radiations makes it possible to carry out industrial chemical processes which cannot be realized by any other methods. Particularly promising is the use of radiation in the production of polymeric materials, i.e., the transformation of monomers into polymers without introducing poly-

merization initiators. Radiation chemistry is also concerned with the study of the stability of various materials under irradiation, the development of methods for protecting them against the effects of radiation, and with finding new ways for synthesizing chemical substances and changing their properties in the desired direction.

Radiation monitoring system. A system of measures worked out specifically for monitoring radioactive radiations and providing safety at enterprises and institutions dealing with irradiation units and radioactive materials (natural and artificial) and also for carrying on continuous control and recording of doses of irradiation of people, radioactive contamination of land, water, atmosphere, foodstuffs, equipment, and structures.

Monitoring is done with the aid of numerous instruments: *dosimeters* indicating the amount of the dose; *röntgenometers* used for determining the dose rate received within a certain time interval; and finally *radiometers* measuring radioactive contamination of the area and the surrounding objects.

Monitoring instruments have a wide range of applications and are designed specifically for each particular purpose: measuring the external radiation background, radioactive contamination of the area, premises and working surfaces, machines and equipment, clothes, hands, footwear soles, and so forth. They may be stationary, portable (down to pocket-size), provided with audio and light signalling devices.

Radiation protection. The great diversity of fields of application of nuclear energy necessitates the manufacture of all kinds of instruments, arrangements, units, and also special clothes to protect personnel dealing directly or indirectly

with radioactive materials and radiations in the course of the long industrial chain—from the processing of the initial raw material to the burying of nuclear industry waste.

A thoroughly thought-out system of interlocked lines of defence against hazards has been elaborated and is constantly being improved: the first line consists of fully automated safeguards (barriers, screens, boxes, locks, containers, monitoring units, etc.), which preclude direct contact with radioactive materials or accidental entry into a zone of hazardous ionizing radiations. It should be remembered that the human sense organs are insensitive to this radiation. That is why the instrumentation of the second line of defence is extremely varied, including so-called *monitoring equipment*—stationary and portable, of most diverse types and purposes. It is designed both for measuring any types of radiation and for detecting hazardous doses of it.

For more reliable safeguarding, use is made of automatic signalling devices, which set off an alarm whenever radiation tolerance levels are achieved.

Since radioactive contamination of the air, clothing, devices and tools is always a possibility, special laboratory instruments—radiometers—are used for inspecting large and small areas suspected of radioactive contamination. If doses exceeding the stipulated limit are detected, the device automatically sends a danger signal.

For personal monitoring use is made of devices recording the cumulative radiation dose received by each worker during a full working day. These are various devices ("*pencils*", *film stacks*, etc.) containing pieces of special photographic film which darkens under irradiation, personal mi-

niaturized "ionization chambers", pocket *electrometers*, etc.

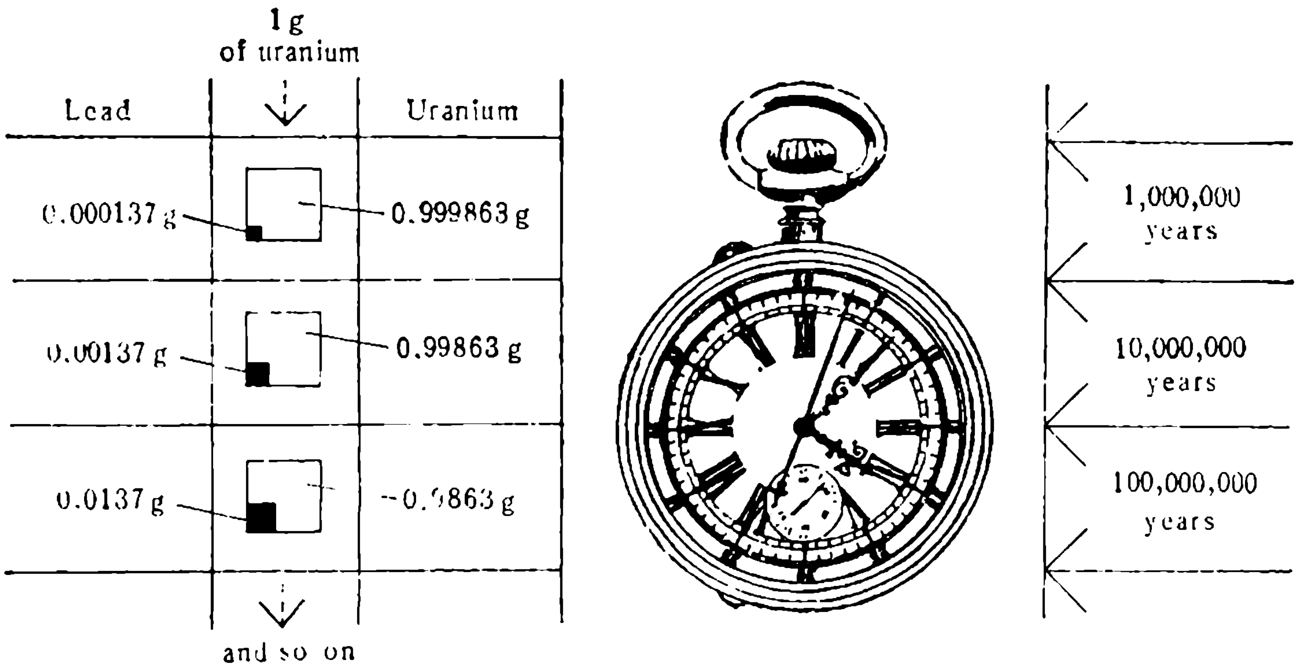
Radiation sickness. A disease caused by external irradiation of an organism with X-, beta- or gamma-rays, neutrons, protons and alpha particles, and also resulting from ingress of radioactive substances into the organism (internal irradiation). The first to suffer from it are the blood-forming organs, mucous membranes, and hormonal glands.

The acute and chronic forms of radiation sickness are distinguished. The acute form may arise when a body receives a large single dose of external irradiation or when a large amount of a radioactive substance finds its way inside it. One and the same radiation dose received by different people may affect them differently depending on the ability of the body to resist radiation. The chronic form is caused by prolonged action of continuous or repeated radiation in small doses, and is characterized by a number of differing symptoms. A system of combined treatment of both the acute and the chronic form of radiation sickness has been worked out, which provides for transplantation of bone marrow in particularly serious cases.

Radioactive dating. If the initial substances of the three series of radioactive elements—uranium, thorium, and actinium—had a comparatively short half-life, they would have long ceased to exist on Earth, and we would not even have suspected today that the familiar element lead had such unusual ancestors.

It is known precisely now that the half-life of uranium-235 is 710,000,000 years, that of uranium-238—4,500,000,000 years, and that of thorium-233 as much as 14,000,000,000 years! And the more precisely scientists determine the decay

rate of radioactive elements and isotopes, the more reliable are the methods for dating, with their aid, the age of rocks. This is an amazing clock going tirelessly for thousands of millions of years without ever being fast or slow and counting its peculiar, infinitely long cosmic time.



Let us assume that uranium-238 has been discovered in a certain mineral. The mineral should unavoidably contain also some intermediate, longer-lived products of uranium disintegration and, no doubt, the end product—a stable isotope lead-206.

It is easy to compute that within a million years 0.000137 g of lead should form in a gram of natural uranium. By careful measurement of the amount of the remaining uranium and of the lead formed it is possible to determine rather accurately (no other methods exist!) the time of formation of the given mineral.

The age of the Earth can be determined more precisely by using the *potassium-argon method*. Natural potassium consists of two stable isotopes—potassium-39 (93.08%) and potassium-41 (6.91%)—and one unstable isotope, potassium-40, whose half-life is 1.3×10^9 years. Potassium abundantly occurs in nature, it enters into the composition of the most important rock-forming minerals. It is also distinguished by very high stability of its isotopic composition.

Radioactive potassium-40 disintegrates in two ways: 88 per cent of its atoms form a stable isotope calcium-40, and 12 per cent transform into an unstable isotope argon-40, which after emitting a gamma quantum turns into the principal, stable isotope argon-40. The decay of potassium-40 gradually leads to its depletion in the natural element and to the accumulation of decay products—argon-40 and calcium-40. By measuring and comparing the amounts of these isotopes it is possible to determine the absolute age of rocks.

Radioactive fall-out (radioactive contamination of the biosphere). Contamination of the atmosphere, area, soil, water basins, and/or various structures by radioactive substances as a result of nuclear explosions or disposal of radioactive wastes of the nuclear industry into the air.

In nuclear bomb explosions in the air large radioactive particles fall out near the explosion site, causing radioactive contamination of the surrounding area, while smaller particles are diffused into the troposphere and stratosphere and carried by air currents all over the globe.

An underwater explosion causes strong contamination of an enormous amount of water which is carried by underwater currents and natural circulation throughout the waters of

oceans. Underground nuclear explosions result in radioactive contamination of the soil in the immediate vicinity of the explosion site and, in some cases, in invasion of the atmosphere by radioactive gases and fission products with their subsequent precipitation on land, as has already happened after underground explosions in the USA.

Radioactive iodine. Natural iodine is a chemical element with an atomic number 53 and an atomic weight of 127 ($_{53}I^{127}$); it has only one natural isotope, iodine-127. However, by neutron irradiation of antimony or tellurium in a nuclear reactor, and also as a result of fission of nuclei of uranium-235 and plutonium-239 it is possible to obtain a whole range of radioactive isotopes of iodine with widely differing half-lives: iodine-125 (56 days), iodine-128 (25 min), iodine-130 (12.6 hr), iodine-131 (8 days), iodine-132 (2.4 hr), iodine-133 (22 hr), iodine-135 (6.7. hr). Radioactive isotopes of iodine are widely used in medicine and biology, mainly for investigation and treatment of disorders in the thyroid gland, which accumulates iodine. The isotope iodine-131 is most suitable for this purpose, since it possesses a short half-life. Its concentration in the thyroid gland may be measured rather accurately externally with the aid of ordinary dosimeters sensitive to the gamma-rays emitted by this isotope.

The healing effect of radioactive iodine, for instance, in cases of cancer or hyperthyroidism, is based on the fact that, having accumulated in the thyroid, its beta-rays destroy the affected or sick secretory cells from within.

When an atomic bomb explodes in the atmosphere, many long-lived isotopes of iodine precipitate in radioactive fall-

out. Finding their way into the bodies of people and animals, they may cause radiation sickness or even death if their concentrations are high.

Radioactive isotopes. The great variety of elements resulting from the fission of uranium and plutonium emit all kinds of radioactive radiations: long-lived and short-lived, strong and weak, single and combined, practically in any combinations. For instance, strontium-90 (5.3% of the total yield) decays by half within 25 years and emits only beta-particles of 0.63 MeV energy, while a daughter element, yttrium-90, forming simultaneously with it, decays by half within only 62 hr, but it emits beta-particles of 2.3 MeV energy. Neither of them emits highly penetrating gamma-rays. Zirconium-95 with a half-life of 65 days emits beta-particles of two kinds: those of 0.39 MeV energy (98%) and a small number (2%) of particles of 1 MeV energy, and at the same time it emits three kinds of gamma-rays of energies 0.73 MeV (93%) or 0.23 MeV (93%), and 0.92 MeV (7%); a daughter element niobium-95 with a half-life of 35 days emits beta-particles of 0.15 MeV energy and gamma-rays of 0.76 MeV energy. Here one can note a law common to all of them: the shortest-lived isotopes possess the highest energy, and conversely, the longest-lived ones have the lowest energy.

Radioactive isotopes are widely used in industry. Radiation intensity varies in accordance with the thickness, density, amount or absorbing power of the substances placed between the radiation source and the counter. Hence, it is rather easy to design a great many devices and apparatuses for determining the thickness of sheet products, for instance, steel, non-ferrous metals, paper or anything whatsoever,

by comparing them with a reference specimen. What is more by connecting, for example, a radioactivity counter to a device controlling the distance between the rolls, on which the thickness of a sheet or band depends, it is possible to maintain automatically the required thickness of the product put out by the machine. It is also possible to control as efficiently the quality or size of articles, the density of solutions, the rate of flow of liquid and bulk materials along pipes, and carry out a host of other similar operations.

Radioactive isotope irradiators very effectively replace X-ray units, especially powerful ones which are used in machine building and metallurgy, where it has become routine practice to gamma-ray huge ingots of metal and finished products in order to detect internal defects: flaws, cracks, foreign inclusions, and others.

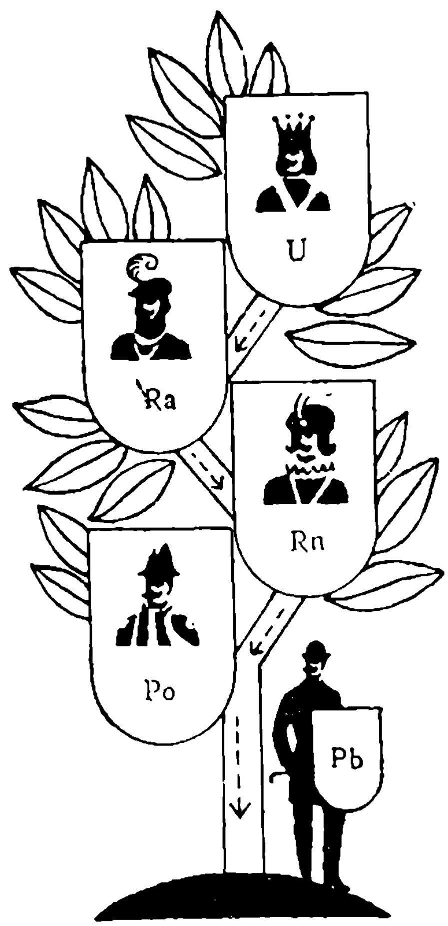
They are much simpler, more convenient and cheaper than the X-ray units of the corresponding penetrating power; they can also cope with steel products up to 250 mm thick.

Radioactive series. A series of elements which form spontaneously from one another as a result of radioactive disintegration is called a *radioactive series*. There are four such series. They embrace all the known natural radioactive elements.

The parent of the first radioactive series is uranium-238, which finally decays to Pb^{206}, an isotope of ordinary lead. The second series begins with thorium-232, which transforms in the long run into the isotope of lead Pb^{208}. The third series proceeds from actinium-235 or actinouranium-235 and ends with lead-207.

The disintegration process occurs as follows. A substance, having emitted an alpha-particle, reduces in mass by four

mass units and turns into a new substance which is located two boxes back in Mendeleyev's Periodic Table of Elements. When a beta-particle (electron) is emitted, however, one of the neutrons is converted into a proton. Since in this



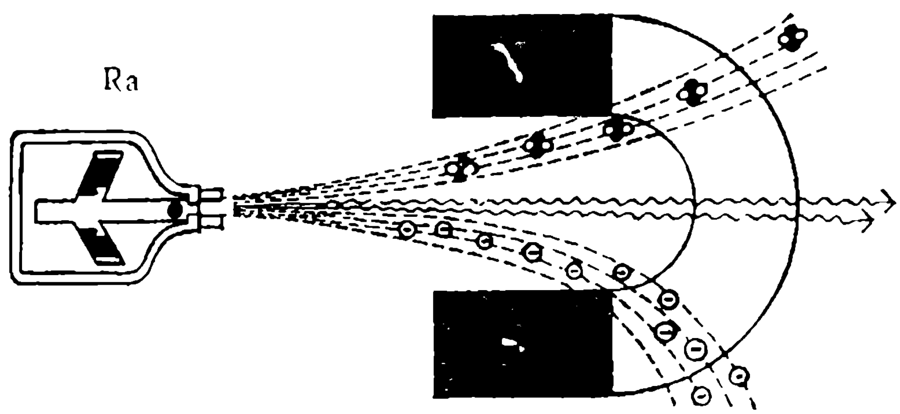
case only a redistribution of the neutrons and protons in the atomic nucleus takes place, this results in its transformation into one of the isotopes of the element standing next in the Table.

The fourth radioactive series begins with the artificially obtained radioactive superheavy transuranium element plu-

tonium-241, then passes into the chain of uranium-235 and ends with thorium-205, which is also stable.

Radioactivity. The spontaneous, continuous disintegration of certain natural and artificial elements, which is entirely unaffected by external conditions and during which these substances emit *alpha-*, *beta-*, and *gamma-rays*. The phenomenon of radioactivity was first discovered in 1896 by the French physicist A. Becquerel and studied in detail by Marja Sklodowska and Pierre Curie, who discovered the most important natural radioactive elements: uranium, thorium, polonium, and radium.

The English physicists Rutherford and Soddy established that, unlike the ordinary elements, the atomic nuclei of



radioactive substances are unstable formations, and therefore they constantly disintegrate. Emitting alpha- and beta-particles (helium nuclei and electrons), they transform into new, lighter elements. For instance, radium-226 ($_{88}Ra^{226}$), by emitting an alpha-particle ($_2He^4$) per atom and losing two positive charges and four mass units, transforms

into a new element, radon-222* ($_{86}Rn^{222}$). As a result, atoms of *two* new elements—radon and helium—are formed. However, this does not stop the process of disintegration of the initial radioactive element. The newly formed radon-222 proves to be unstable too and, losing in turn an alpha-particle, produces a new, also unstable radioactive substance—polonium-218 ($_{84}Po^{218}$). This process of successive disintegration and formation of generations of radioactive substances ceases only when the entire initial amount of radium finally turns into ordinary lead, more precisely, into one of its isotopes—lead-206 ($_{82}Pb^{206}$).

Radioactivity, artificial. The radioactivity artificially created in stable chemical elements by irradiating them with neutrons in nuclear reactors or by bombarding these elements with heavy particles—protons, alpha-particles, etc.

Because of the vast diversity of their properties (type of radiation, energy, half-life, mass of emitted particles, and so on) the radioactive substances obtained artificially are used much wider than natural ones (see *Isotopes*). In connection with the discovery of artificial radioactivity it became possible to realize the dream of mediaeval alchemists—to turn atoms of some chemical elements into atoms of other elements (see *Radioactivity*).

After this discovery scientists in different countries began bombarding all the chemical elements in Mendeleyev's Table with nuclear particles. It has been found that almost

* Rutherford was the first to show that radium and its compounds slowly evolve a gas which he called radium emanation. This gas is now known as radon.—*Ed.*

all of them can form new artificial radioactive isotopes. Within a comparatively short time the number of such radioactive isotopes reached a thousand, and new isotopes are discovered each year.

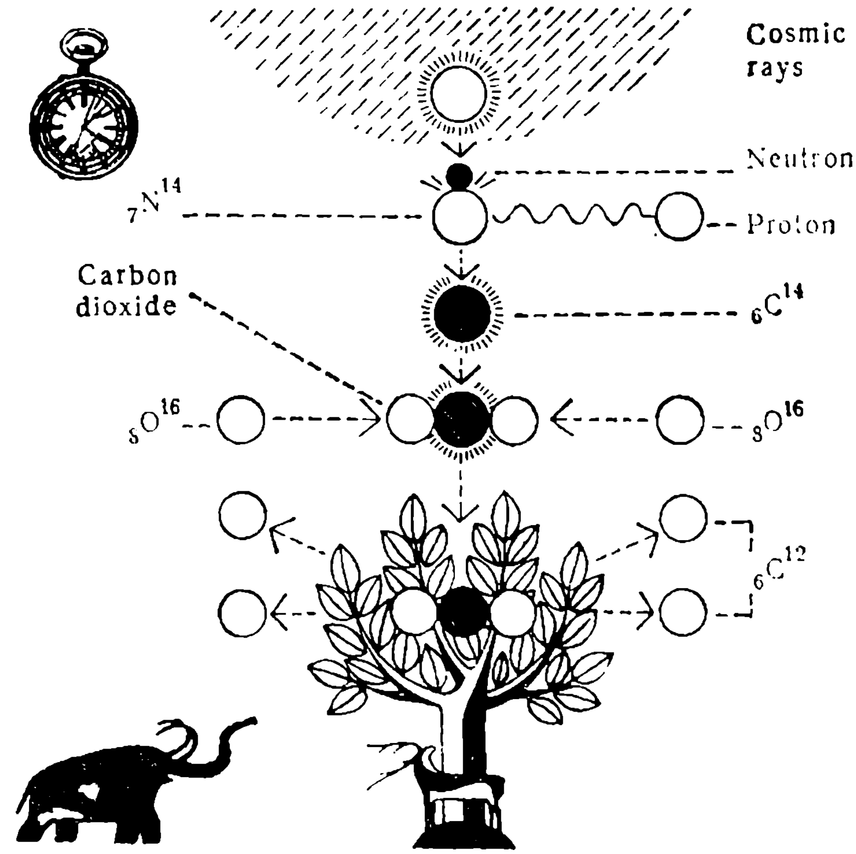
Artificial radioactive isotopes now occupy an extremely important place in science and engineering.

Radiobiology. The section of the biological sciences dealing with changes in animal and plant organisms under the effect of ionizing radiation. Radiobiology is concerned with the study of the primary mechanisms of action of ionizing radiation on living cells, injuries and irreversible changes in cells, of the complications caused in organisms by this radiation, and also of the hereditary changes manifested in the progeny of irradiated organisms.

Radiocarbon dating. Astronomers, geophysicists and geologists count in terms of hundreds of millions and thousands of millions of years. Other scientists are interested in shorter periods of time—thousands of years. Here one has to resort to a method which, strange though it may seem, is of cosmic origin—the application of the radioactive isotope of carbon, C^{14}, as a geological clock.

Natural carbon, whose compounds form the basis of all living organisms, consists of two stable isotopes: carbon-12 (98.892%) and carbon-13 (1.108%). Another, radioactive isotope of this element, carbon-14, which is of extraterrestrial origin, is detected in very negligible quantities in the atmosphere. Where does it come from?

Our planet is subjected to continuous bombardment with cosmic rays—particles possessing a tremendous energy measured in tens and hundreds of millions of millions of electron-volts (see *Cosmic rays*). These particles break up



1	50 thous. mil. atoms of $_6C^{14}$
1/2	25 thous. mil. after 5,570 years
1/4	12.5 thous. mil. after 11,000 years
1/8	6.25 thous. mil. after 22,000 years

atomic nuclei of air they encounter on their way, forming neutrons along with the fragments. The neutrons are captured by the nuclei of other atoms, including nuclei of nitrogen-14. A nuclear reaction takes place with the formation of the isotope carbon-14 with a half-life of 5, 570 years.

Carbon is also one of the most active chemical elements in nature. For this reason, once formed, carbon is "attacked" by oxygen atoms and, combining with them, forms carbon dioxide, CO_2.

The omnipresent wind and also the mutual diffusion of the gases intimately mix the molecules of the gas, containing the trace of radioactive carbon atoms, with molecules of ordinary carbon dioxide.

Then everything follows its usual course: carbon dioxide is taken up by plants, and then animals and people use these plants as food together with the radioactive carbon assimilated by them.

Let us now assume that at a certain time and in a certain place an animal got sick, stopped taking food, and died. Or a tree was felled. After the lapse of 5,570 years an archaeologist or palaeontologist, while making excavations discovered a bone of this animal or a piece of wood from a structure. After the death of an animal or plant the incorporation of radioactive carbon ceases and the carbon-14 already present slowly decays away. Half of the initially accumulated carbon-14 will disappear within 5,570 years, half of the remaining amount within another 5,570 years, and so on. But what amount of radioactivity should be considered as initial? The point is that the content of the "cosmic" isotope in ordinary natural carbon has not changed during millions of years, because a balance between the newly

formed and disintegrating atoms of carbon was established in nature long ago.
Consequently, it only remains to determine the difference between the radioactivity of the carbon-14 detected in the fossils of animals and plants and its radioactivity in the living matter around us.
Any animal or plant living today contains the same number of carbon-14 atoms in 1 g of tissue carbon as an animal or tree which died 5,570 years ago, namely about 50 thousand millions of atoms. But the number of these atoms in their fossils has reduced, say, by half. This means that the animal or tree died 5,570 years ago. If only 1/4 of the radioactive atoms remain, we can say that the age of these fossils is 11,000 years, and so forth.
This method has been verified on tissues taken from Egyptian mummies and on other archaeological finds whose time of burial was known precisely.

Radiochemistry. A branch of science dealing with the problems of production, separation, purification, and determination of radioactive substances, and also with the methods of measuring their principal properties, and the chemistry of nuclear reactions in which radioactive elements appear and disintegrate. Radiochemistry employs unique methods, differing from those of ordinary chemistry, since radioactive radiation makes it possible to use many physical methods of analysis with the aid of various particle counters.
Radiochemical analysis is characterized by high accuracy and sensitivity. No other method would have permitted, for instance, determination of the chemical properties of

one of the artificial transuranium elements consisting of only ... 17 atoms! Applied radiochemistry also studies the methods for the application of radioactive isotopes in ordinary chemical research.

The present-day stage of development of radiochemistry is closely related with the utilization of nuclear reactors both as a neutron source and as a means for the production of artificial radioactive isotopes of any elements with most diverse physical properties, and also with the use of high-energy accelerators which enable artificial transuranium elements to be obtained.

In connection with the development of a powerful nuclear industry radiochemistry also deals with the study and design of technological processes for the production of initial radioactive materials, restoration of the nuclear fuel spent in reactors, separation of fission products, and with many other problems.

Radiography. The general name of the methods for recording and studying ionizing radiation (charged particles and gamma-rays) with the aid of photography. When a charged particle or gamma-quantum enters a layer of photoemulsion, it leaves a track of ionized atoms. The result is the formation in the grains of the silver bromide contained in the photoemulsion of centres of a latent image which become visible (darken) after the plate or film is developed. By using this method it is easy, for instance, to obtain the pattern of distribution of radioactive indicators (*tracer atoms*) in a particular substance over the whole surface area or cross section of the object under investigation. To do this, the photographic plate is simply placed for some time against the object (for instance, a plant leaf, a metal

plate or a tissue section). In the same manner it is possible to investigate any forms of surface phenomena—adsorption, corrosion, and so on, and also the processes of formation and growth of crystals and the distribution of the components in metal alloys.

Radium, Ra. A natural radioactive element, one of the first to be discovered and isolated in pure form (by Marie and Pierre Curie at the end of the 19th century).

This substance proved to be virtually amazing. It continuously emits invisible rays of enormous penetrating power. Under the effect of these mysterious rays, as well as under the action of X-rays, screens coated with zinc sulphide, platinum barium cyanide and other substances glow in the dark, and photographic plates become fogged.

Negligibly small amounts of this element, not exceeding 1,000,000,000ths of a gram, can be detected by the ionization of the air caused by their radiation. The new radiation exerts a strong effect on living organisms and in many cases becomes hazardous to people's health. All these extremely unusual properties are responsible for the name "radium" (radiant) that was given to it by its discoverers.

Radium is the product of disintegration of a series of elements beginning with uranium-238 and it has four natural isotopes with mass numbers 228, 226, 224, and 223 (the average atomic weight is 226.05). The longest-lived isotope radium-226 emits alpha-particles with 4.78 MeV energy and a half-life of 1,617 years. The emission of alpha-particles is accompanied by gamma-radiation with 0.188 MeV energy. Due to the high energy of the emitted alpha-particles radium, together with polonium-210 (whose alpha-particle energy is still higher, 5.3 MeV), for a long

time (until charged-particle accelerators and nuclear reactors were built) represented the "main projectile of the atomic artillery" for bombarding atomic nuclei of all light elements in Mendeleyev's Periodic Table. It is with their aid that the possibility of transmutation of some elements into others was discovered, the existence of the neutron established, and most of the important discoveries of the atomic age made. Gamma-rays of energy 190 keV emitted by radium served for a long time as the only means for treating the most dreadful human disease—cancer, and also for flaw detection in metal objects, etc.

Range of a particle. The path traversed by a charged particle until it slows down to a stop as a result of numerous elastic collisions with atomic nuclei of the substance in which the particle is moving. The range depends on the energy (velocity) of motion of the particle, its charge, mass, and also on the properties of the substance (medium). The range increases with the particle energy, and with a given velocity it is approximately proportional to the particle mass and inversely proportional to the square of its charge. The range is usually expressed not in units of length, but in mass units of the layer of the substance traversed by the particle (g/cm^2).

Reactors. *Uranium-graphite reactor.* The first, now classical, basic type of nuclear reactor in which the nuclear fuel is arranged in the neutron moderator—graphite blocks. Due to the low neutron absorption in graphite, reactors of this type possess a rather high thermal utilization factor and are widely used in industrial units designed both for plutonium production and the generation of electric power.

Water-water reactor. A nuclear reactor in which the neutron

moderator is ordinary distilled water, which also serves as heat-transfer agent, the medium removing the heat from the reactor to the heat exchanger.

The water-water reactor produces slightly larger quantities of plutonium than other reactors, the reactor power being the same.

Fast(-neutron) reactor. The general name of nuclear reactors in which the fission of the nuclear fuel—highly enriched uranium-235 and plutonium-239—is effected by fast neutrons of energy 1 MeV and higher. Such a reactor contains no moderator. Fast-neutron reactors are usually small in size, but have a large fuel charge. There are a number of designs of such reactors, for instance, the *pulsed reactor*, the *fast breeder reactor*, etc.

Pulsed reactor. Imagine two pieces of plutonium (their mass being slightly less than the *critical mass*) so placed that a slot is left between them which is sufficient to preclude a nuclear chain reaction. In this slot a disc with a piece of uranium-235 attached to it is rotating at a speed of 5,000 rpm. During the negligibly short time when the piece of uranium-235 finds itself between the pieces of plutonium, the mass of the entire combination of nuclear fuel becomes *supercritical*, and an explosive chain reaction is started. Then... No explosion will occur, because a tiny fraction of a second before the expected explosion the piece of uranium escapes from the slot and the chain reaction dies out just as rapidly. But at the moment of "opposition" of the plutonium and uranium a beam of fast neutrons is ejected like a flash of lightning.

The importance of this reactor lies in the fact that at an average power level not exceeding 1 kW it "shoots" out

neutron pulses of several thousands of kilowatts each at a frequency of five thousand times per second, which can only be done by a large industrial reactor.

All this makes it possible to study and measure not only the energies, velocities, and properties of great masses of neutrons, but also the results of their interaction with various substances.

Fast breeder reactor. We have already mentioned that the fissionable isotope of uranium, U^{235}, constitutes only 0.7% of natural uranium. Formerly the remaining 99.3% of uranium-238, after a very complicated process of isolating uranium-235, was actually dumped into waste and did not find any application in other branches of industry. For some time this "waste" was stored and nobody knew what to do with it.

The scientists were faced with a new problem: which is the most advantageous and technically simple way of liberating the energy hidden in the depths of the atom—by the direct method, in which the valuable fissionable isotope uranium-235 is separated from natural uranium (see *Separation of isotopes*) or by the initiation of a self-sustaining chain reaction of fission of uranium-235 in an unseparated natural mixture of uranium? If we artificially slow down the neutrons ejected in the fission of atomic nuclei of uranium-235 to a velocity at which most of them will be eagerly absorbed by nuclei of uranium-238, then, after undergoing a short series of radioactive disintegrations, the nuclei of uranium-238 will turn into nuclei of the radioactive element plutonium-239, which does not exist in nature and which is fissioned by neutrons of any energies, from thermal to fast.

What do we lose in this process? By burning 0.7% of uranium-235 out of the natural mixture it is possible to convert a smaller amount of uranium-238 (0.3-0.5 of the 0.7%) into plutonium-239.

And what do we gain by it? Although the mass of plutonium-239 is close to that of uranium-238, chemically it is quite a different element, with different properties, and it is incomparably easier to separate it from fission fragments and unfissioned atoms of uranium-235 and from uranium-238 which has not turned into plutonium-239, than to carry out a still more costly, time-consuming and complicated process of physical separation of uranium isotopes.

The scientists selected the second, more rational method, and the utilization of nuclear energy in industrial and power plants became a reality. This tremendous achievement of science and technology, however, has not solved the basic paradoxical problem: only 1/140th of the total mass of natural uranium can be utilized with the aid of fast neutrons, whereas the rest of it has to go to waste.

But how and where can we get a sufficient number of fast neutrons to fission the remaining 139/140ths of uranium-238?

Only much later was it established that, unlike uranium-235, a great number of neutrons ejected in a chain reaction of fission of plutonium-239 possess the necessary energy for fissioning atomic nuclei of uranium-238. Why then do we not try to build a nuclear reactor which would use not the fission of uranium-235, but fast neutrons ejected during the fissioning of plutonium-239, approximately along the following lines. We would place in the centre of the reactor a core made up of plutonium rods in which we would

initiate a controlled nuclear fission chain reaction accompanied by abundant emission of fast neutrons. In place of the graphite reflector returning the neutrons into the reactor core, we would install a few rows of rods of uranium-238, which would completely absorb all fast neutrons that reach them and soon transform into plutonium-239.

Assume that 1 kg of plutonium-239, which was previously obtained somewhere by the conventional method, will "burn down" in the reactor. Each atom of this plutonium, having split into two parts, will shoot out two or three fast neutrons of energy exceeding 1 MeV. On the average, say, one neutron will be spent to maintain the chain reaction in the plutonium, while from 1.5 to 2 neutrons will get stuck in the nuclei of the uranium-238, turning them first into neptunium-239 and then into plutonium-239. In the long run, about 0.5 to 1 kg of plutonium-239 will appear in the uranium reflector.

If this one kilogram of plutonium-239 is recharged into a similar reactor, then already 2 kg of uranium-238 will turn into plutonium. In short, instead of 1/140th of natural uranium, it will be possible to use several times as much, and in the future even all of it!

The very small size of the reactor core in which, however, hundreds of thousands of kilowatts of thermal energy are liberated, extremely complicates the removal of such a great amount of heat from it.

Intermediate(-neutron) reactor. A nuclear reactor in which the fission of atomic nuclei of uranium is caused by neutrons of intermediate energies, from 1 keV to 0.5 MeV.

Thermal(-neutron) reactor. Any type of nuclear reactor in which the predominant number of fissions of the nuclear

fuel occur by capturing slow (thermal) neutrons, for which purpose use is made of moderators (water, graphite, heavy water) reducing the energy of the neutrons to about 0.03 eV.
Enriched-uranium reactor. A nuclear reactor using nuclear fuel with artificially increased content of the fissionable isotope uranium-235. When enriched fuel is used the multiplication factor increases to such an extent that the reactor designer can use materials which absorb a larger number of neutrons than special materials (for instance, stainless steel with ordinary water) as moderator. Besides, the somewhat higher content of the isotope uranium-235 enables the critical mass of the uranium fuel, and hence the size of the reactor, to be reduced.
Zero-power reactor. A nuclear reactor of such a low power that it does not require forced cooling or any special measures for protecting the personnel from radiation. Such reactors are only used for research, experimental, and educational purposes.
Gas-cooled reactor. A nuclear reactor in which, instead of water or liquid metal, the heat-transfer agent is a gas which is a poor neutron absorber. Gas cooling makes it possible to obtain very high temperatures at the reactor outlet which are needed to increase the efficiency of the unit, but it requires considerable expenditures of energy for pumping a great volume of gas.
Reactor with an organic moderator and heat-transfer agent. In a nuclear power station operating on the steam-water cycle the reactor is not the heaviest component of the equipment. The lion's share of the weight falls on the biological shielding (hundreds and thousands of tons), as it has to screen not only the comparatively small reactor core, but the enti-

re bulky structure of the primary circuit, including the piping, pumps, heat exchangers, etc. Only the heat-transfer agent and piping of the secondary circuit and the turbines remain unshielded.

Heavy shielding is essential because no matter how ideally pure the water passing through the reactor core may be, it "absorbs" the radiations: the negligible amounts of salts and certain isotopes of oxygen dissolved in it become highly radioactive and hazardous to personnel in the vicinity of the reactor. Besides, the water entering the reactor core heats up to temperatures of the order of 450 to 550°C and higher, and to keep it from boiling it must be placed under an enormous pressure of 100 to 150 atmospheres. All this creates considerable difficulties in designing reactors.

Let us now try and see what happens if, instead of using water or capricious and rather dangerous liquid metals (see *Liquid metals*), we chose a moderator (and heat-transfer agent) which does not become radioactive under radiation of any intensity and at the same time has a higher heat capacity than water. Then we could dispense with the bulky and heavy biological shielding and all that is outside the reactor core and thus reduce the weight of the biological shielding by 25 per cent or maybe even by half.

As a compromise between water, which requires excessive pressure, and chemically active and hazardous liquid metals, use is made of certain organic compounds such as polyphenyls: diphenyl ($C_{12}H_{10}$), terphenyl ($C_{18}H_{14}$), and others. These, like liquid metals, do not require high pressures, do not become radioactive to any appreciable degree, because they do not capture neutrons; these materials do not corrode the structural elements of the reactor and are rath-

er resistant to heat and radiations, although their heat-removing ability is much inferior to that of liquid metals and water. The advantages of these compounds also include the small size of the primary circuit, the lower strength requirements for the structural elements and piping of the reactor, and so forth. No doubt, they have serious drawbacks as well. These are the high cost of organic heat-transfer agents, the trend towards decomposition and polymerization under the effect of high temperatures and radiations, which requires the use of an additional circuit where the compound could be regenerated (purified and restored) from time to time.

In the 750-kW mobile nuclear power station *Arbus* designed in the USSR and intended for remote and sparsely populated regions use is made of a conventional diesel fuel—gas oil—as heat-transfer agent. When thoroughly freed from impurities, sulphur in the first place, gas oil is entirely "indifferent" to the effect of radiations and is completely harmless after leaving the reactor core.

Due to this the weight of the whole installation does not exceed 360 tons. The small size of the biological shielding makes it possible to break the power station down into 19 separate blocks ("packages") none of which weighs more than 20 tons.

The efficiency of present-day heat-and-power stations is usually between 38 and 43 per cent of the fuel calorific value, whereas for nuclear power stations it ranges from 25 to 35 per cent, and only in the most efficient stations commisioned very recently it reaches 39-41 per cent. Therefore in all power calculations relating to the use of nuclear reactors as a heat source for electric power stations designers usually

distinguish between the power output of the station in kilowatts, and the heat output of the reactor proper which is usually three to four times the power output of the station. For example, the heat output of the reactor (or reactors) of a 1-mil. kW (1,000-megawatt) electric power station should be from 3 to 3.5 million kW.

Power reactor. A nuclear reactor whose main function is to produce heat for generation of electric power.

Heavy-water reactor. A nuclear reactor using heavy water as moderator. This type of reactor is particularly suited for scientific research, since it enables a very great number of neutrons to be obtained in the core.

Pool(-type) reactor. A nuclear reactor with fuel element assemblies placed on the bottom of a large pool in which the water serves simultaneously as core coolant and neutron moderator. This reactor is mainly used for research purposes and for the production of radioactive isotopes.

Liquid-fuel reactor. A nuclear reactor in which the nuclear fuel is used in liquid form—as a solution of uranium or plutonium salts or as a fine suspension of fissionable materials in some other liquid. The liquid in which the nuclear fuel is dissolved or suspended serves both as neutron moderator and heat-transfer agent removing the heat from the core. This type of reactor has the advantage that the removal of fission products and of the unused part of the nuclear fuel and the introduction of fresh fuel can be effected gradually and continuously without stopping the reactor for recharging. This advantage, however, complicates the reactor design and hinders its operation, since continuous recovery of the fuel requires addition of a special assembly in which part of the fissionable material circulating

through the reactor should always be held. For the same reason the size of the biological shielding should be considerably increased.

Heterogeneous reactor. A reactor in which the nuclear fuel and the moderator are arranged at a certain distance from each other in a regular geometrical pattern consisting of separate blocks, thus representing a heterogeneous medium for neutrons.

Homogeneous reactor. A reactor in which the nuclear fuel and the moderator are mixed to form a homogeneous medium. This may be a mixture of fine powders or a suspension of fine particles.

Recombination. Re-uniting atoms into molecules of the substance that has been disintegrated (dissociated) under the influence of external forces, such as very high temperatures.

Recording chambers. The name given to a whole class of devices which, along with particle counters and thick-emulsion photographic plates, represent the basic means for observation and recording of nuclear reactions, transformations of elementary particles in their interactions, and for studying these transformations and reactions not only from the qualitative, but also from the quantitative point of view. Among the great variety of such devices the most important are: the *Wilson cloud chamber*, in which a flying charged particle leaves behind a visible track of condensed supersaturated vapour; *bubble chambers* based on the property of a superheated liquid to boil when a charged particle passes through it, leaving a visible track in the form of tiny vapour bubbles; *spark chambers*, in which the appearance of a particle is announced by a microscopic electric discharge, and many others.

Resonons. Unusually short-lived (about 10^{-24} sec) particles discovered in 1962 with the aid of new gigantic accelerators simultaneously in the USSR and the USA. Because of the extremely short mean life of resonons the scientists are inclined to regard them not as a peculiar sub-family of elementary particles, but rather as a certain instantaneous intermediate and extremely unstable form of existence of "normal" elementary particles.

Rest mass. The mass of an atomic particle whose velocity is zero or is assumed to be zero. In ordinary usage the rest mass is often confused with weight.

Röntgen, r. A quantity very important in nuclear engineering, which indicates the degree of ionization of a substance under the effect of X-rays or gamma-radiation, or, what is the same thing, the amount of radiation absorbed by the substance. The röntgen is equal to that quantity of radiation at which in 1 cm^3 of air at normal atmospheric pressure (760 mm Hg) and 0°C there appear charges (ions) of both signs equal to one electrostatic unit each. One röntgen corresponds to 2.1 million pairs of ions in 1 cm^3 of air. To produce one pair of ions in air each radiation photon spends 32.5 eV of its energy. The amount of radiation measured in röntgens is important for determining safe radiation doses to which living organisms may be subjected.

The doses of ionizing radiations other than X-rays or gamma-radiations (alpha- and beta-particles, protons, neutrons, etc.) are measured in units called *röntgen equivalents physical* (*rep*). But since the biological effect of such particles on living organisms is different, it is measured in other units called *röntgen equivalents man* (*rem*).

Röntgen rays (X-rays) possess a high penetrating power and may cause the darkening of a photographic plate and a glow in certain substances, they ionize gases and exert a biochemical effect on living cells. These properties are used in science and technology for X-raying opaque objects (e.g. steel ingots up to several tens of centimetres thick) in order to detect flaws in them, for X-raying patients, treating malignant tumours, investigating the chemical composition of substances, stimulating plant growth, for agricultural pest control, and so on.

S

Scintillation. Scintillation counters. Under the effect of ionizing radiations in certain organic and inorganic substances and their solutions, for instance, in zinc sulphide, calcium tungstate, terphenyl solution in toluene and others, flashes of light occur, which are called *scintillation.* These substances are often called *phosphors.*

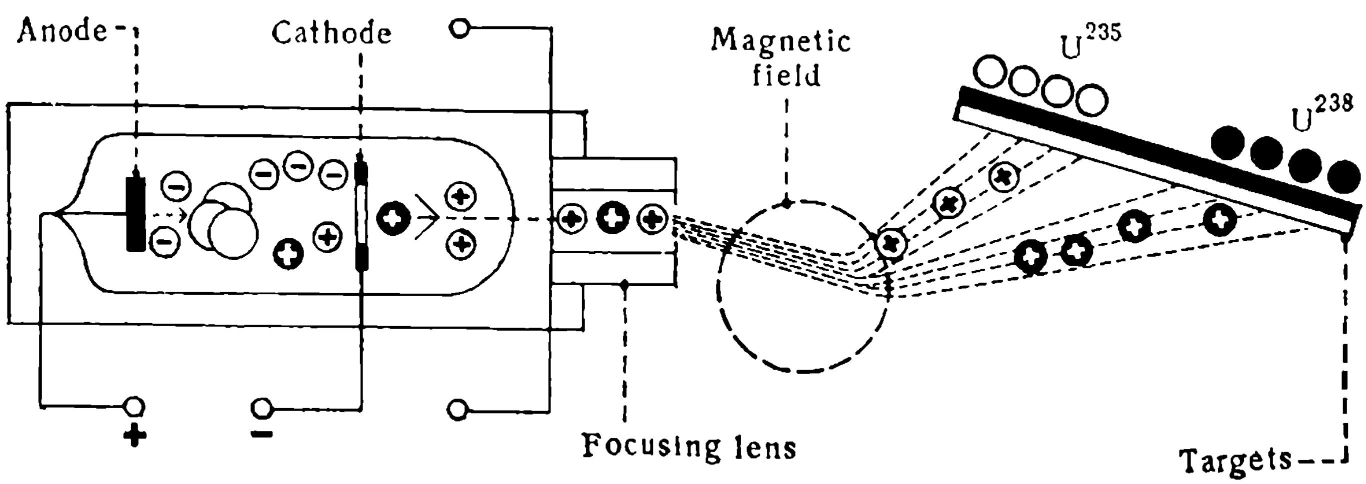
If we connect a crystal to a highly sensitive multistage light amplifier (*photomultiplier*), then each scintillation flash, which is again greatly amplified with the aid of a valve amplifier, can actuate any kind of computing device. Scintillation counters are highly sensitive to all types of radiation. Since it is difficult to manufacture very large crystals which are sometimes required for nuclear experiments, use is made of liquid scintillating solutions of solid organic and inorganic scintillators in benzene, xylene, to-

luene, and other solvents. However, the efficiency of solutions is slightly lower than that of pure crystals. Solid solutions of scintillators in polystyrene, plexiglas and other transparent plastics have been developed; they have considerable advantages over liquid solutions.

Separation of isotopes. Ways for partial or complete separation of a mixture of different isotopes of one and the same chemical element. Such separation cannot be effected by chemical methods, since the chemical properties of isotopes of one and the same element are absolutely identical. An electric field will not help either, because the number of electrons in the shell and the positive charge of the nucleus are quite the same in all of them. What can be done then? Fortunately, isotopes differ in their mass. This property is used in so-called *mass-spectrographs*—"atom-sorting machines", laboratory devices for determining the mass of atoms.

If a certain amount of gaseous substance (an isotopic mixture subject to separation) is placed in an evacuated tube with two soldered-in electrodes to which a high voltage is applied, the following picture can be observed. Any volume of gas always contains a certain number of free electrons knocked out of atoms as a result of collisions. Under the effect of a strong electric field set up by the anode these free electrons will immediately rush to the anode. Colliding with neutral atoms of the gas on their way, the electrons, which have already developed a high velocity, will ionize them, i.e., knock out new electrons. The knocked-out electrons, which have also become free, will in turn rush to the anode and on their way will tear their portions of electrons away from the atoms they encounter. As a result,

an electric current will flow through the tube, its intensity depending on the extent of ionization of the gas.
How will the positive ions—atomic nuclei of the gas—behave? They will rush in the opposite direction, towards the cathode of the tube, also with a high velocity, but much slower than the electrons, because their mass is several thousand times that of the electrons.
If we make an opening in the tube cathode, then part of the ions accelerated to a high velocity will jump through this opening and emerge from it as a narrow ion beam. It is possible to interpose several annular electrodes in the path of such a beam, and apply an additional negative voltage to them in order to increase the ion velocity still



further. Then the ion beam will enter a strong magnetic field. Any charged particle, interacting with a magnetic field, changes its direction. Naturally, ions having different masses will deflect differently under the effect of the magnetic field. The lighter the isotope, the more the path of the ion will be deflected. If we now interpose a slightly negatively charged target—a metal plate—in the path of

the ion beam, each kind of ions will be deposited at a different spot of the plate.
By repeating this operation many times it is possible to separate the element into its component isotopes to any degree of purity. This principle lies at the basis of a rather complicated instrument—*Aston's mass-spectrograph*, named after its inventor, an English physicist.
With the aid of this device scientists have investigated almost all chemical elements in Mendeleyev's Periodic Table; they found a small number of isotopes in some elements and a dozen or more isotopes in others (see *Isotopes*).
But it is one thing to separate trace amounts of isotopes and another to collect a sufficient amount of them for the manufacture of an atomic bomb or for utilization in a nuclear reactor.
The following method proved to be more efficient. It is known from physics that molecules of any gas mixture have on the average the same kinetic energy. This by no means indicates that all of them move with the same velocity. Some molecules move more rapidly as a result of numerous collisions, others move more slowly, and the lighter molecules generally move faster than the heavier ones.
The light molecules, which move faster, impinge, therefore, more frequently on the walls of the vessel containing the gas mixture, thereby creating a higher pressure in it, and the heavier molecules create a lower pressure. If one of the vessel walls is made of a substance with a great number of micropores, after some time a slightly greater number of light molecules of the gas will have escaped outside than of heavy ones. The gas leaked out and collected outside will

prove somewhat lighter than the gas remaining in the vessel. This selective infiltration of the lighter molecules of gas through the porous walls of a vessel is called *gaseous diffusion.*

However, this (incidentally very slow) process is used in practice only when the lighter gas penetrates through the partition in one direction, namely outwards, and cannot return inside. Therefore the vessel should consist of two compartments. In the first compartment the gas is under a slightly increased pressure, and it is continuously driven off from the second compartment. If we make up a battery of a great number of such vessels divided by a porous partition and make the mixture to be separated pass successively through all these vessels (cells), say, through several thousands of them, at the end of this tiresome journey only the lightest of the gas molecules will be left.

To use this method for separating the isotopes of natural uranium, it must be converted into a gas. The only gaseous compound of uranium is uranium hexafluoride, which is used for the separation of a natural mixture of the isotopes uranium-238 and uranium-235.

There are several other methods for isotope separation, for instance, centrifuging, separation in a supersonic jet escaping from a nozzle, and others, but they are not developed sufficiently as yet and therefore do not find wide application.

Spark chamber. A counter for recording radioactive radiations in which a charged particle, when flying in a carefully adjusted gap between two electrodes under a high tension, ionizes the gas or another substance filling this gap with the result that whenever a charged particle appears,

an ordinary electric discharge (electric spark) occurs between the electrodes. A device attached to the chamber makes it possible to count the number of discharges per unit time and hence the number of charged particles flying through the spark gap.

Spin (of an electron). Apart from the energy associated with its rotation around the atomic nucleus, an electron possesses an additional energy (*intrinsic angular momentum*) due to its spinning about its own axis, similarly to a toy top. This energy is called the *electron spin.* Since an electron carries an electric charge, its rotation sets up a ring electric current and hence a magnetic field as well, which turns the electron into a tiny electromagnet with two magnetic poles. Since an electron can rotate in different directions, clockwise and counterclockwise, it can be in two different energy or spin states. The electron spin gives rise to a number of additional interactions which play an extremely important part in the physical properties of the atom.

Other elementary particles—protons, neutrons, and photons (radiation quanta)—also possess a spin. According to the laws of the quantum theory the spin has a strictly defined value characteristic of a given particle. In the system of units adopted in the quantum theory the spin of each electron, proton, and neutron is equal to 1/2. The spin of the photon is unity.

Sterilization of foodstuffs. The ability of radioactive radiations to suppress vital activity and kill some pathogenic bacteria and other parasites made it possible to devise several methods for sterilization of foodstuffs not only in a prepared state but in the raw state as well; examples are

raw meat, fresh fish, etc. In medicine, radiation sterilization is used for the disinfection of surgical instruments, dressing materials, culture media in microbiological research, drinking water, and so forth.

Stimulating effect of radiations. Some scientists believe that the effect of very small doses of radioactive radiations on cells and living organisms does not suppress their vital activity, but, on the contrary, enhances their basic vital functions; for instance, it speeds up plant growth. Numerous investigations, however, do not confirm this viewpoint, at least as far as animal cells are concerned. The results obtained in respect to plant cells are extremely conflicting and therefore this problem is being carefully studied in many research institutions of the world.

A certain enhancement of the vital functions of an animal body as a whole under the influence of small radiation doses, for instance, on taking radon baths, is not the result of the increased function of individual cells under a direct effect of radiation, but is attributed to certain radiation-induced changes in the functions of the nervous and endocrine systems of man which, in turn, affect the basic functions of the cells; in other words, indirect stimulation of the vital activity of the cells is achieved.

Strontium, Sr. A chemical element with an atomic number of 38 and an atomic weight of 87.63. It is an alkali metal. Strontium has four stable isotopes: strontium-84 (0.56%), strontium-86 (9.86%), strontium-87 (7.02%), and strontium-88 (82.56%).

During the fission of uranium nuclei a whole family of radioactive isotopes of strontium is formed, chiefly strontium-89 with a half-life of 50.5 days which emits beta-particles

of energy 1.463 MeV, and strontium-90 (27.7 years) which emits beta-particles of 0.61 MeV.

Strontium-90 has become notorious as a dangerous fall-out which precipitates onto the ground after atomic bomb explosions. Dissolving in water, it is absorbed by plants, which are then consumed by domestic animals, after which the strontium finds its way into the human body with the milk. Owing to its affinity for calcium, strontium-90 deposits in human bones, causing continuous internal irradiation of the bony tissue and bone marrow.

Because radioactive isotopes of strontium emit beta-rays (electrons), they are widely used as labelled atoms (tracers) in scientific research, in chemistry, industry, and engineering. Strontium-90 and its daughter isotope yttrium-90 are used as electron sources in nuclear batteries.

Synchrocyclotron (frequency-modulated cyclotron). A charged-particle accelerator using the so-called principle of the *phase stability* of orbits proposed by the Soviet scientist V. Veksler. The basic idea is that under certain conditions and with a proper selection of accelerating electric and controlling magnetic fields one can accelerate each particle so that, in spite of its possible individual deflections, it will acquire a pre-assigned maximum energy at the end of its path. This is achieved, for instance, by gradually reducing the frequency of the accelerating voltage applied across the accelerating gap in order to compensate for the *relativistic effect* (increase in particle mass at near-light velocities), which is the principal cause of violation of synchronization in the cyclotron.

The frequency is changed so that the voltage pulses arrive at the accelerating gap with increasing delay after each cir-

cuit of the particle, in strict accord with its relativistic "gain in mass" and gradual reduction in acceleration rate.

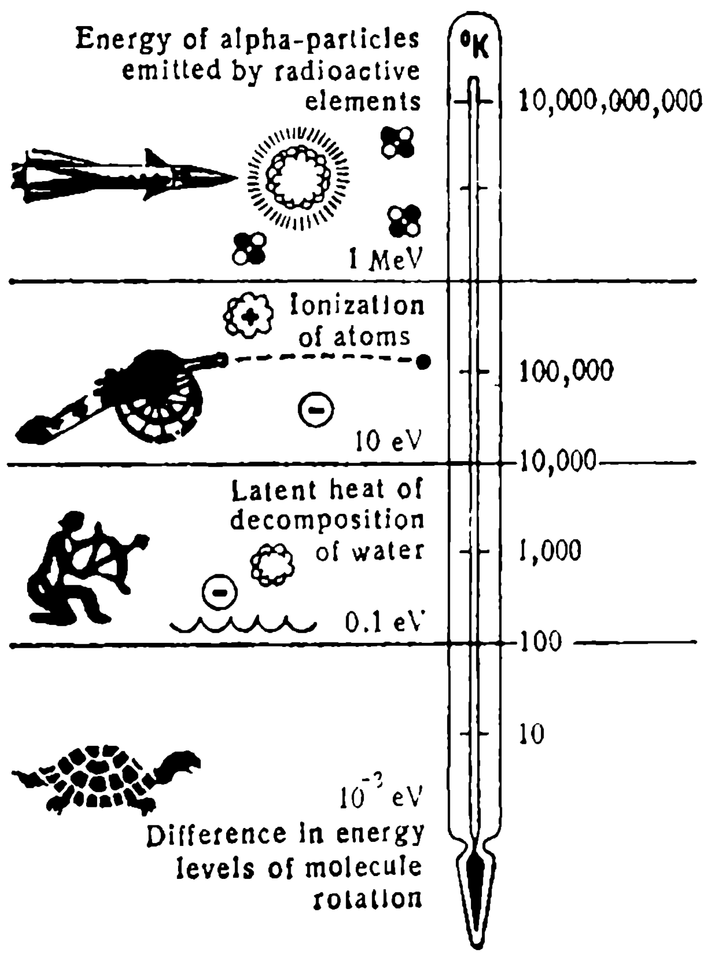
T

Temperature. The measure of the random motion of an aggregate of particles manifested in the form of thermal energy. Thermal energy is the kinetic and potential energy of individual molecules of which all bodies are made up. A high temperature corresponds to a high level of thermal energy. At a high energy level and, consequently, at a high temperature, particles move more rapidly and, on encountering other particles, collide with them more energetically and more frequently. At a low energy level and temperature the particle velocity and the number of collisions are smaller, of course.

The temperature of a body or a substance is determined by the average energy of an aggregate of particles of which the given body or substance is composed. But wherever random, chaotic motion of particles prevails, one can naturally find particles of widely differing energy, i.e., moving with most diverse velocities.

This brings us to the following conclusion: to each energy of a particle or a set of particles there corresponds its own velocity of motion, and hence a definite number of collisions with other particles and, as a result, a definite temperature. Therefore, in order to judge the state of a substance it is important to know the average energy of its particles.

And the temperature of a set of these particles is only a consequence of their average kinetic energy.
Careful measurements of particle energy levels show that to an energy of particle motion equal to 1 eV there corresponds a temperature of 1000°K. To rip, say, an electron away from a hydrogen atom, it is necessary to spend 13.53



eV of energy. Thus, to achieve the same result solely by heating atoms of a substance, their temperature should be raised far above 10000°C. Such is the relation between energy expressed in electron-volts and energy expressed in degrees Celsius.

Most of the molecules of a substance disintegrate into atoms (dissociate) at a temperature of 10000°C. The atoms lose the greater part of their outermost electrons or all of them at 100000°C and, finally, the atomic nucleus disintegrates into protons and neutrons at a temperature exceeding thousands and tens of thousands of millions of degrees. All these processes are accompanied by the absorption of the energy spent on overcoming the attractive forces holding together the primary building blocks of an atomic nucleus, then atoms, and finally molecules.
To carry out a thermonuclear reaction, we already need energies of several tens of thousands of electron-volts. In this case the gas is heated to several hundreds of millions of degrees. This figure is amazingly great, but it tells little to the physicist, who is ultimately interested not in temperature, but in particle energy.
The chief characteristic of thermal energy is that it is the energy of random motion and collisions of particles, chaotic motion in all directions, irrespective of time.
Quite a different physical picture is observed in the motion of a flux of particles in a vacuum, all of them moving in the same direction, for instance, the motion of particles boosted to an energy of, say, 1 GeV (one thousand millions of eV) in accelerators.
It would have seemed that at such energies the temperature of the gas consisting of these particles should reach ten thousand millions of millions of degrees Celsius. This is not observed in reality, however, because the motion of the particles is of an orderly nature. They all move in the same direction, rarely colliding with each other, this sharply differing from the random thermal motion of particles which

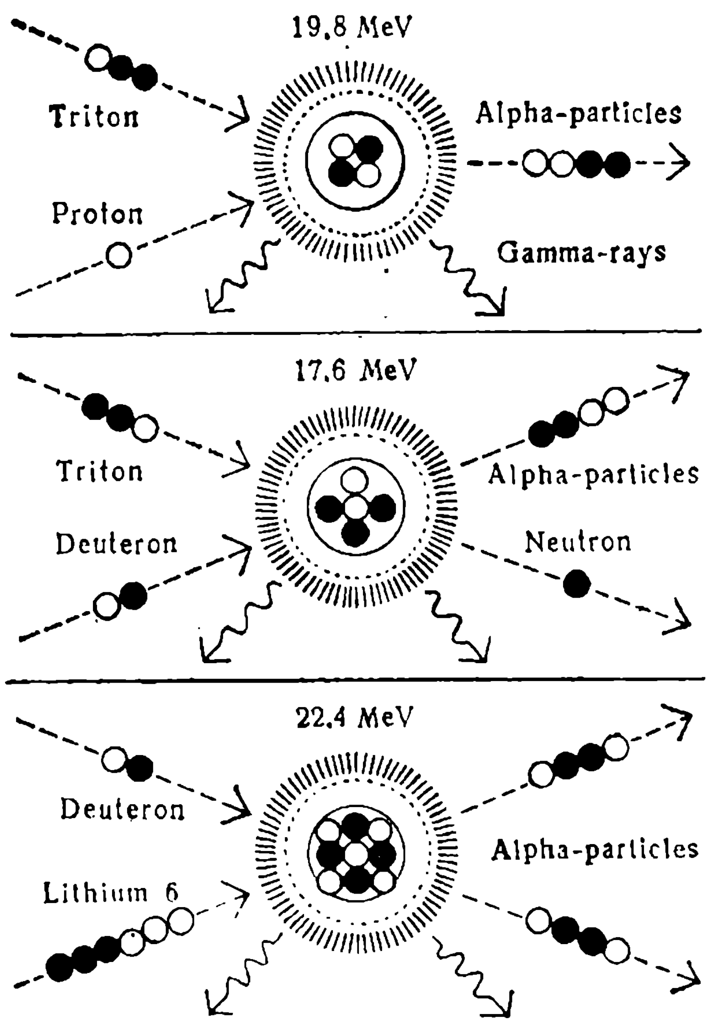
would take place in a gas at this velocity of the component particles. Therefore we can successfully determine the energy of these particles (which is just what we need), but we can say nothing about the temperature of this particle flux. This is actually immaterial, since this temperature will be moderate. At the same time we can accurately indicate the temperature of an aggregate of these particles when they hit a target, i.e., when their orderly motion turns into a random one. This temperature will be equal to thousands of millions of millions of degrees.

Thermal (slow) neutrons. This name was given to neutrons whose kinetic energy is comparable with the thermal energy of the molecules of the environment at room temperature (20°C), which corresponds to an energy of 0.03 eV. Because of their ability to fission readily atomic nuclei of uranium-235 and plutonium-239, thermal neutrons play the main part in the process of initiation and propagation of a nuclear fission chain reaction carried out in nuclear reactors (see *Controlled chain reaction of nuclear fission*).

Slow neutrons are obtained artificially as a result of repeated elastic collisions with atomic nuclei whose mass is close to that of the neutrons, for instance, atomic nuclei of hydrogen, helium, deuterium, and carbon which absorb very few neutrons, if any at all. In each of these collisions the neutron loses part of its kinetic energy to an atom of this substance and therefore its velocity decreases until an energy particularly favourable for fission of uranium-235 nuclei is reached.

Thermonuclear reaction. Let us take the hypothetical case of formation of an atomic nucleus of helium, ${}_2H^4$, by the fusion of two nuclei of heavy hydrogen, ${}_1H^2$. We say hy-

pothetical because this reaction is, as explained below, more difficult to carry out so far than other reactions. The energy of 23.64 MeV liberated in this reaction represents the difference between the total binding energy of the



atomic nucleus of helium (28.2 MeV) holding the four nucleons together and the total binding energy of the two nuclei of heavy hydrogen (2.28 MeV each) holding only two nucleons in a nucleus.

Thus we can see that the liberation of such an enormous amount of energy requires considerable "expenses". There

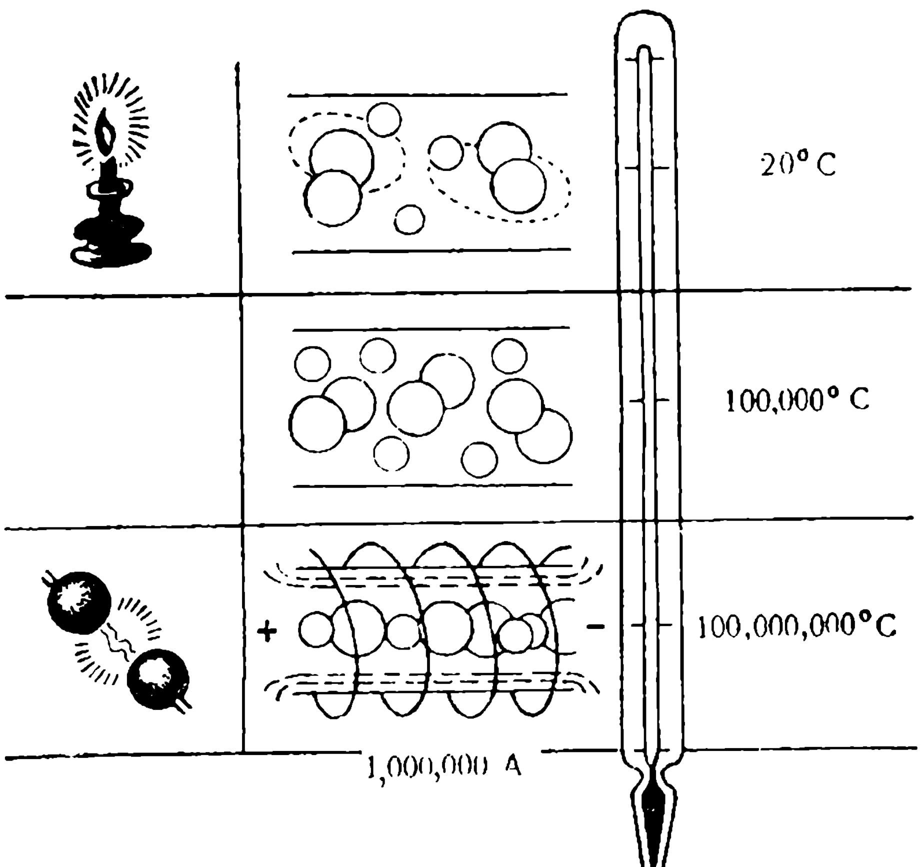
is nothing surprising in it. The most unpleasant thing is the following: the fusion of two nuclei of heavy hydrogen is possible provided only that the energy of each of them is at least 20 keV. This energy can be acquired by them only if deuterium is heated to a temperature of the order of 200 millions of degrees Celsius! This is a lot considering that at room temperature the thermal energy of air particles is only 0.25 electron-volt! (see *Heat*, and *Temperature*). Only at this temperature, which exists exclusively in the depths of very hot stars, will it be possible to overcome the mutual repulsion of two positively charged nuclei of heavy hydrogen and to "push" them into the sphere of action of other, still more powerful and already *attractive* nuclear forces.

Two hundred millions of degrees! Such heat is even difficult to imagine. Nevertheless, man succeeded in achieving it in a comparatively simple way by exploding a "conventional" atomic bomb inside a shell filled with substances most readily entering into a thermonuclear reaction. For a very brief instant—millionth fractions of a second—the temperature inside the shell reached several hundreds of millions of degrees, and pressure, millions of millions of atmospheres. As a result the hydrogen nuclei began to fuse into atomic nuclei of helium with a release of energy, followed by a second, still more powerful explosion!

Since it is possible to fuse atomic nuclei of light elements (e.g. hydrogen) into nuclei of heavier elements (e.g. helium) and to obtain the particle motion energy necessary for this purpose only at temperatures of hundreds of millions of degrees, while all substances turn into a plasma even at lower temperatures, it becomes quite clear why, after many years of investigations, the scientists arrived at the conclu-

sion that the solution of the problem of a controlled thermonuclear reaction should be sought among the numerous mysteries of the plasmatic state of matter.
All things we say about plasma elsewhere in this book are rather theoretical than practical considerations, because nobody has ever observed the behaviour of a plasma confined in a vessel at a temperature of 200 to 400 millions of degrees, except for the flash of an atomic or hydrogen bomb. And the reason is quite simple: such vessels do not and cannot exist. They would have evaporated and disintegrated not only into atomic, but into nuclear particles.
But even if we could find such a vessel, all the same a plasma could never be heated there to such a high temperature. Why?
There is a law in physics according to which the ability of a heated body to give off heat rises abruptly with temperature. According to the *Stefan-Boltzmann law*, radiation is proportional to the fourth power of the temperature. Therefore any attempts to heat a plasma to a temperature at which fusion of nuclei of heavy hydrogen into those of helium would begin are doomed to failure. On reaching the equilibrium temperature all the heat supplied to the plasma will be transferred to the vessel walls, which in turn will generously dissipate it into the environment.
We will recall that all the foregoing speculations were hypothetical, since we have not mentioned the most important point: where can we get a heat source capable of heating our plasma to the temperature of the depths of a star—200 millions of degrees?
Quite unexpectedly, the lightning came to the rescue.
A gas in a cool state is an excellent electrical insulator but

only up to a point. Already at a comparatively moderate voltage a so-called *gas discharge* may take place in a highly rarefied gas. One of the "junior members" of the tremendous family of gas-discharge devices is the familiar neon light. But what will happen if we try to discharge a bank of condensers charged to a colossal voltage—of the order of five to six million volts—through a tube filled with a rarefied gas and possessing a tremendous strength?



Such a man-made lightning, several metres in length, although it cannot be compared with a natural lightning in its destructive force, will make it possible, for an extremely

brief instant (thousandths of a second), to concentrate in a very small gas volume an enormous energy sufficient to turn the gas confined in the tube into a plasma by heating it to the temperature of the surface of the Sun—several millions of degrees.

What is a gas discharge in a tube filled with a rarefied gas? It is an orderly (for a short time) motion of electrically charged particles—free electrons, all moving in one direction, and of positive ions moving in the opposite direction.

And what is an orderly motion of electrons? It is an electric current. We know that a ring-shaped magnetic field is set up around a conductor along which an electric current flows. And the stronger the current, the stronger will be the magnetic field. If such a current flowing in one direction is passed through a bunch of parallel conductors, the magnetic field will immediately press them together with a great force. An ideally ionized plasma is actually a rather loose bunch of conductors.

If this is the case, the annular magnetic field set up around the tube and continuously growing with intensity of the current flowing through the plasma begins to compress the loose plasma column into a thin pinch, reducing its volume and thereby increasing further its temperature and pressure, since the number of mutual collisions of the atomic particles in the small plasma volume rises abruptly. And, what is the most important thing, the magnetic "fist" compressing the plasma tears it away from the tube walls, stopping the dissipation of heat through them. This, in turn, raises the plasma temperature still higher. And if the energetic bombardment of the tube walls with the storming particles stops, then the pressure on them is released, and the

insolvable problem of manufacturing tubes with fantastically strong walls ceases to exist.

In short, a plasma organizes itself: it compresses, heats up, and completely isolates itself from the tube walls. Consequently, only one problem remains: to "drive" as much energy as possible into the plasma by increasing the voltage and intensity of the electric current and the magnetic field set up by it around the plasma. And then ... wait until the initiated thermonuclear reaction destroys the whole installation and everything for miles around?

Nothing of the kind, of course, will or can happen. In the first place, a plasma is created in a comparatively negligible volume of a strongly rarefied gas. And even if an explosive thermonuclear reaction were initiated throughout its volume, the explosion would be of limited intensity and safe at any rate.

Further. The gap between the temperatures that can be obtained by heating a plasma in this way and the 200 millions of degrees required for a fusion reaction is still very great.

True, if we use, in place of deuterium alone, a mixture of deuterium and tritium, the temperature needed to initiate a thermonuclear reaction will be substantially lower, and the reaction will be possible even at thirty to forty millions of degrees.

But how can we ascertain that such a reaction has taken place during the discharge? From the appearance of neutron radiation. On fusion of two atomic nuclei of heavy hydrogen (deuterium) a nucleus of the isotope helium-3 is formed and a proton or neutron is ejected, and at the same time gamma-radiation is given off and an energy of 3.2 MeV liberated.

If one of the deuterium atoms is replaced by an atom of superheavy hydrogen (tritium), a helium nucleus (alpha-particle) is formed and one neutron and some gamma-quanta are emitted. In this case 17.6 MeV of energy is released. The fusion of an atomic nucleus of tritium with a proton yields an alpha-particle and an energy of 19.8 MeV and, finally, in the synthesis of a nucleus of lithium-6 with a nucleus of heavy hydrogen two alpha-particles are produced and an energy of 22.4 MeV is released.

By trapping the neutrons ejected from the plasma and determining their number it is easy to establish everything we need to know about the plasma: the number of nuclei participating in the thermonuclear reaction, its rate of propagation, and so on.

Unfortunately, a magnetic field has not proved to be an ideal invisible wall confining a plasma in the centre of the tube. First, it may happen that individual particles of the plasma, colliding with each other in infinite combinations of velocities and energies, will accidentally acquire such a high energy that they will ultimately be forced through any, even the strongest magnetic field, towards the vessel walls.

Secondly, under certain conditions a great number of charged particles, moving together and in the same direction at a certain moment may set up a magnetic field of their own capable of squeezing the plasma out through the confining magnetic field. A plasma may play other tricks, too. Why are the scientists so "touchy" about such freaks of plasma?

The point is that a controlled thermonuclear reaction does not begin in a plasma as it does in a hydrogen bomb, i.e.,

with an explosion which lasts only millionths of a second and less. The time of particle fusion depends on the "density" of the plasma. There is a definite maximum of "density" which can confine a given magnetic field. If a plasma is brought to this "density", then the fusion time will be approximately one second. Thus, it is necessary to "thermoinsulate" the plasma—maintain its temperature—at least for a second or maybe for a little longer. And this is very difficult.

Since a straightforward way (an electric discharge in a gas) does not yield the desired results, and a plasmatic state can be obtained by other methods as well, scientists began to test all these methods one after another. It is well known that if a particle accelerated to a high velocity gets into a magnetic field it goes into a "spiral", and the more intensive the magnetic field, the more energetically it will spiral. The particle "winds up" on a magnetic "line" of force which it encounters on its way. This line is invisible, and its composition is still unknown. Such a line is rather imaginary than real.

Let us shoot a beam of electrons or positively charged ions of deuterium from the side into a large, thoroughly evacuated tube surrounded by huge coils which set up a strong magnetic field inside it. The particles will immediately begin "spiralling" along the lines of this field, colliding with each other and heating up. If we now increase the intensity of the magnetic field, then, while compressing, it will in turn begin to compress the "garlands" of charged particles wound around the lines of this field. The number of their collisions will increase, and so will the plasma temperature. If we set up a still stronger magnetic field at the ends of this

tube—*a magnetic trap*—the charged and spiralling particles will rebound from it and start moving back, only to spiral back again on encountering an identical magnetic wall or "mirror" at the other end of the wall. Thus the particles will swing to and fro along the lines of the magnetic field, accumulating energy under the effect of the magnetic field and raising the temperature of the entire plasma. An installation has been built, which operates on this principle. This installation named "Ogra" has been developed at the I. Kurchatov Institute of Atomic Energy.
Plasma particles can also be made to move along an annular tube by compressing it with a *longitudinal* magnetic field. To improve the characteristics of this "doughnut", it may be twisted once more to obtain a figure of eight. This will be a *stellarator*, which is the main object of plasma research in the USA.
There are many other types of similar installations.
Thorium, Th. A heavy natural radioactive chemical element with an atomic weight of 232.05 and an atomic number of 90. Metallic thorium consists practically of a single isotope—thorium-232, since the other 13 isotopes taken together account for less than 1%.
Of all the natural radioactive elements thorium has the longest half-life, 14,500,000,000 years!
Although thorium, along with uranium, is considered to be nuclear fuel, it is impossible to initiate a chain reaction in it because of the absence of a fissionable isotope, such as uranium-235 in ordinary uranium, which is fissioned both by fast and slow neutrons. Therefore, thorium cannot be used for power production in its usual state. But why then is it considered such a valuable nuclear fuel along

with plutonium? Because thorium-232, as well as non-fissionable uranium-238, can readily be transformed into nuclear fuel. To this end it should first be subjected to intensive neutron bombardment in a nuclear reactor of an ordinary or special type. After two disintegrations, which are accompanied by the emission of beta-particles, thorium-232 turns into an artificial uranium isotope, uranium-233, which does not exist in nature and which, like plutonium-239, is fissioned both by fast and slow neutrons.

Tracer atoms. In practice, there are hundreds and thousands of cases where the successful solution of a particular scientific or technical problem completely depends on the knowledge of where a certain substance is located, from where and how it has arrived or where it has gone. A metallurgist, for instance, will be interested to know why the presence of even small amounts of sulphur makes a metal brittle and weak. A small amount of the radioactive isotope of sulphur is incorporated into a metal. A study of photographic films obtained under the action of beta-particles emitted by such *labelled atoms* shows that the sulphur impurities are located mainly along the boundaries of the crystals of the metal, which was the cause of the abrupt decrease in its strength. It is vitally important for a biologist to trace the path of certain nutrients in a living organism, the delicate processes of their assimilation, the action on the organism of some drugs or other preparations. The phenomena under study become much clearer when we add to atoms of these substances a small amount of entirely identical, but radioactive atoms. Their movement in the organism is continuously traced with the aid of a variety of counters and other detecting devices.

The addition of radioactive isotopes to alloys used in the manufacture of cutting tools or heavy-duty machine parts enables us to establish rather easily the degree and nature of their wear, the dependence of the wear on additions to the alloys from which these parts and tools are made, on the quality of lubricants, the temperature, speed and other conditions of operation.

Tracks. Traces of elementary particles recorded on photo-emulsions in *recording chambers* (Wilson cloud chamber, bubble chamber and others).

Transuranium elements. The attempts of E. Fermi and his young colleagues in the mid-thirties to create new chemical elements still heavier than uranium by bombarding it with neutrons at first led the scientists rather far astray from their main course, and only after completing their round of honour full of sensational discoveries, which lay through light fragments of uranium-235, did they succeed in discovering new, genuinely superheavy transuranium artificial elements—neptunium-239 (No. 93) and plutonium-239 (No. 94). However, attempts to obtain still heavier elements failed, since it was found that the energies and properties of any particles at the disposal of the scientists, including the almighty neutron, were not sufficient for the purpose. And it was not until the advent of powerful accelerators, which speeded up particles to energies of hundreds and thousands of millions of electron-volts, that new artificial transuranium elements began to appear one after another; they had atomic numbers from 95 to 104: americium-243 (1945), curium-247, berkelium-247, californium-249, einsteinium-254, element No. 100 named after E. Fermi, fermium-253, element No. 101 starting the second hundred

and named after the great Russian chemist Mendeleyev, mendelevium-256, nobelium-254 and, finally, recently discovered lawrencium-257, and kurchatovium-264. This group of elements has not been sufficiently studied so far. They are all radioactive and extremely short-lived: the higher the atomic weight, the shorter the mean life. They do not occur in natural rocks on Earth. Some of these elements were obtained in such negligible amounts (17 atoms!) that the highly refined facilities of modern radiochemistry were required to determine their properties.

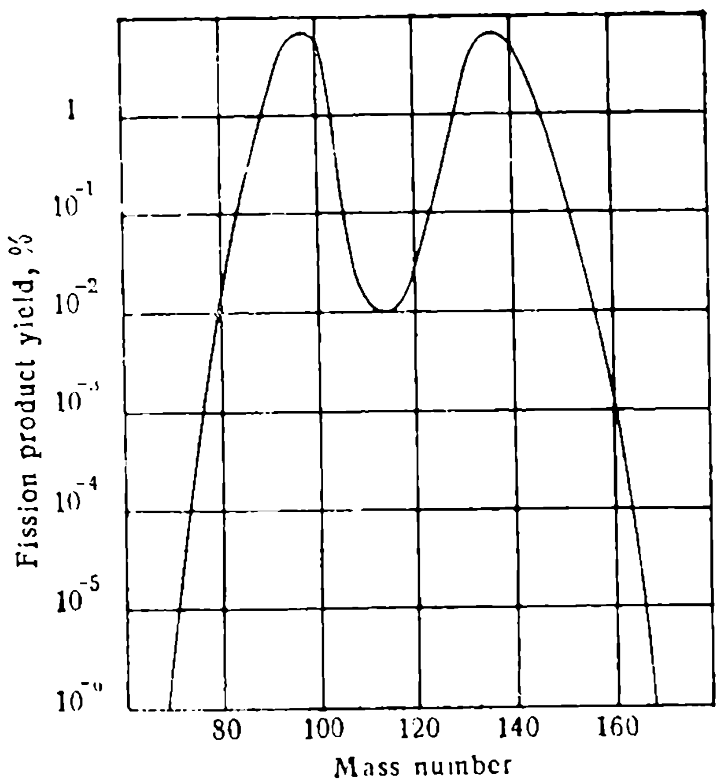
Tritium. A superheavy radioactive isotope of hydrogen with an atomic weight of 3. The atomic nucleus of tritium consists of one proton and two neutrons. The half-life of tritium is 12 years. On disintegrating, the atomic nucleus of tritium emits beta-particles with an energy of about 0.018 MeV.

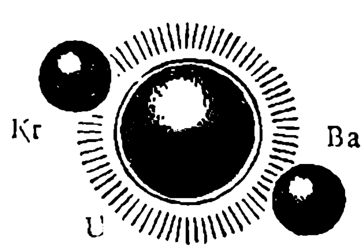
Triton. The atomic nucleus of tritium (superheavy hydrogen). It consists of three nucleons: a proton and two neutrons.

U

Uranium, U. A radioactive natural element with an atomic number of 92 and an atomic weight of 238.07. Uranium is a silvery metal, it is readily machinable, its melting point is 1130 °C. Uranium eagerly oxidizes in air, ignites in a normal atmosphere at a temperature of about 100 °C. It has three isotopes: uranium-238 (99.27%), uranium-235

(0.72%), and uranium-234 (0.006%). Uranium-238 and uranium-235 are the parents of the families of natural radioactive elements which, after a long series of successive





disintegrations, turn into stable isotopes lead-206 and lead-207. The half-life of uranium-238 is 4,500,000,000 years, that of uranium-235—710 millions of years, and uranium-234—250 thousand years.

Quite a number of uranium isotopes can be obtained arti-

ficially, but the most important of them is uranium-233, which forms as a result of neutron bombardment of thorium-232. Uranium-233 is fissioned equally readily by fast and slow neutrons.

Uranium fission products. When an atomic nucleus of uranium-235 splits in two in the course of a nuclear reaction, the radioactive fragments produced are never equal in size: one is a little larger than the other. Both turn out to be atomic nuclei of elements having masses from 72 to 162—from germanium to hafnium. The percentage distribution of these elements has the shape of a curve with two clearly defined humps relating to masses of about 90 and 140, for instance, strontium-90, krypton-91, yttrium-91, zirconium-95, iodine-126, cesium-137, barium-142, cerium-144, and so on. However, the maximum amount of any one isotope of these elements does not exceed 5-6% of the total number of fragments. The great variety of combinations of radiation types (beta-particles and gamma-quanta), particle energies and half-lives opens up inexhaustible possibilities for the widest application of these elements in science, technology, medicine, industry, and agriculture (see the picture on p. 252).

V

Vacuum. The physical world surrounding us, including the infinitely great number of atoms, nuclear particles, and radiation photons, does not occupy too much space as

such. There exists between them a certain medium, which was once called ether and later received a more correct name "vacuum".

In physics and technology by a vacuum is meant a rarefied gas such that the mean free path of its chaotically moving particles (until they collide with other particles or with the walls of a vessel) exceeds the size of the vessel containing the gas. The pressure of this gas is usually of the order of 10^{-6} to 10^{-7} mm mercury. Even at these pressures, however, one cubic centimetre of the gas contains about 3×10^{10} to 3×10^{9} atoms.

Nuclear physics research requires a considerably deeper vacuum, of the order of 10^{-10} to 10^{-14} mm Hg. But in this case, too, one cubic centimetre of a gas will still contain about 10^{6} particles.

The deepest vacuum in nature exists in outer space. One cubic centimetre of the medium may contain as few as 1 to 3 particles, and this vacuum is a million times (or more) as high as the best vacuum ever obtained by man with the aid of the most perfect evacuating arrangements.

Therefore some electronic devices installed in equipment sent up into outer space do not have to be first evacuated and hermetically sealed. It will suffice to connect them with the outer space and they will be evacuated to such a high degree of vacuum as will evidently be unattainable on Earth for a long time to come.

Van de Graaf generator. The earliest charged-particle accelerators used Van de Graaf generators to set up the necessary high voltage. Due to their simple design and the comparatively high voltage produced, these generators are

still used in laboratory practice for high-voltage and nuclear research.
The operating principle of the generator is based on the fact that if electric charges are sprayed continuously onto a well-insulated conductor by means of, say, a rapidly moving endless belt made of a good dielectric (silk, rayon or rubberized fabric), the electric potential of the conductor will gradually rise to a very high value, which is limited only by insulation. To prevent this, the conductor is made in the shape of a large sphere, while the entire internal part of the arrangement, in which the belt moves and the charges are transferred, is filled with a gas compressed to 15 atmospheres.
The charges are sprayed onto the belt from a row of needle points connected to a 5- to 10-thousand volt source of steady voltage in the form of a power-pack. The belt transfers these charges into the sphere, where they are picked up by another row of needle points connected to the sphere. The practical maximum of the voltage produced by such a generator is 8 to 10 million volts. However, the current obtained from it under load usually does not exceed 1 milliampere.

W

Water desalination. In connection with the population explosion and the rapid development of industrial production, scientists and economists in various countries more and more often calculate and recalculate for different rea-

sons the time during which man will avail himself of the known reserves of mineral wealth, primarily fuels, considering that their consumption has reached a colossal figure—4 to 5 million tons per year!
The scientists' forecasts proved to be worse than gloomy. According to their calculations the available petroleum reserves will last 25 to 50 years at the most, those of coal 200 to 300 years, and only the reserves of the fissionable materials—uranium and thorium—can put off the threat of imminent power famine for a few centuries, or maybe milleniums, and this, in turn, inspires the hope that long before this last power source is exhausted mankind will at last harness the thermonuclear reaction, a practically inexhaustible power source (see *Thermonuclear reaction*).
In recent years, however, quite apart from these forecasts, scientists have been sending real danger signals. Mankind, it appears, is threatened from quite unexpected quarters, and the danger is quite real even *today*: it is the shortage of the mineral most common on our planet—water!
The threatened areas are not the desert, arid and backward regions of the globe where water is sometimes sold at a high price in jugs and cups; quite the contrary, they are highly industrialized and rich countries such as the USA, England, the GFR, and others.
At the slightest caprice of nature: a dry or hot summer, heavy floods in spring, long rainless spells, etc., limitations have to be imposed on water consumption by industrial establishments and the population of large cities.
Just because water covers 71 per cent of our planet, fills the lakes and rivers, falls from above as rain, and saturates the atmosphere with moisture, most people believe

that water sources on Earth (which comprise 1,359,000,000 cubic kilometres of it) are practically unlimited and inexhaustible. And surely, these people imply fresh water. Alas, the predominant part (99.683 per cent) of this mass is the salt water of the oceans.

It is only natural that scientists and engineers more and more often turn their attention to the world's oceans with their vast reserves of water which are now utilized only for transport purposes and are unfortunately unsuitable for use either in technology or for drinking. A new, extremely important and urgent problem has arisen—that of desalination of sea water.

As far back as the year 350 B.C. Aristotle described successful experiments on removal of salt from sea water. Roman legions of Julius Caesar learned to distil water in the year 49 B.C. And although quite a few centuries have elapsed since then and many methods of water desalination have been developed, they all require the expenditure of large amounts of power, about one kilowatt-hour per cubic metre (ton) of sea water—in some cases slightly more, in others slightly less.

In order to begin the struggle for the elimination of the already existing shortage of fresh water people need tens and hundreds of thousands of millions of tons of sea water and consequently as many kilowatt-hours of electrical energy. It should be remembered that fresh water must also be supplied to desert and arid regions of many countries which were once blooming orchards. As a rule, a desert suffers mainly from the shortage of power rather than from the lack of rainfall.

Each country attempts to crack this nut in its own way,

but all their efforts run up against the same problem—where and how to get the necessary amount of energy. The only possible solution lies in the use of nuclear power stations with reactors of extremely high heat output so that they could drastically cut the cost of the electric energy generated.

The first plant of this kind with a rated heat output of over a million kilowatts is under construction in the Soviet town of Shevchenko on the East coast of the Kaspian Sea.

The heat produced by the reactors will be utilized by a 150,000-kW electric power station, while the steam (after having actuated the turbines and the electric current generators) will be directed to a desalting unit producing up to 120,000 tons of fresh water per day, not to mention the valuable chemicals that can be obtained from the brine formed by desalination of the sea water. These amounts of electric energy and fresh water will cover the needs of a large industrial city with a population of several tens of thousands of people!

The combined use of the richest source of power on Earth, nuclear energy, and the unlimited water reserves of the world's oceans will exert a decisive effect on the further progress of civilization.

Whole body counters. All life-forms on our planet contain radioactive isotopes of various elements: uranium, radium, potassium, carbon, etc., and also products of their disintegration. Therefore the human body possesses radioactivity of its own. The most abundant element in the body is potassium-40, which is accumulated primarily in muscular tissues.

This radioactivity is extremely small in absolute value, but it may vary within a rather wide range, depending on a number of factors: the altitude above sea level, the nature of the surrounding area, the food and water consumed, precipitations, and so on. On the average, this activity is equivalent to 200,000 disintegrations per minute and can be measured with the aid of special devices. This level of radioactivity, which is called the *background*, is accepted as the natural dose to which man has adapted himself during the millions of years of his evolution.

The radioactivity of the human body, however, may increase to a harmful and even dangerous value under certain conditions: in space flights, as a result of radioactive fall-out, in the proximity of a nuclear reactor, when working in a "hot" chemical laboratory and handling radioactive isotopes, on introduction of isotopes into the body, on over-exposure, and so on.

This necessitated the construction of monitoring units for systematic measurements of the content of radioactive elements in living organisms.

The radioactivity of the human body is measured in a chamber thoroughly shielded from external radiations by means of heavy steel plates containing no traces of radioactive elements. The measuring device is a scintillation counter or a whole row of such counters made of potassium iodide sensitized with thallium and mounted a certain distance above the body (see *Scintillation. Scintillation counters*). These counters are sensitive to the weakest radiations and are used whenever very weak and also cumulative radiations (alpha-, beta-, and gamma-rays) have to be measured. When the radiation level is sufficiently high or when only

more powerful gamma-radiations are to be measured, the body is placed in a cylinder with hollow walls containing a scintillating liquid. The degree of glow of the liquid serves to determine the total gamma-radiation of the human body.
Since the measuring techniques are very complicated, their results are merely comparative, a definite radiation level being adopted as a standard.

X

Xenon, Xe. Xenon "poisoning". Xenon is element No. 54 in the zero group of Mendeleyev's Periodic Table. It is a heavy inert gas with an atomic weight of 131.3. The natural gas consists of a mixture of nine isotopes of atomic weight from 124 to 136. When uranium-235 is fissioned in a nuclear reactor, ten radioactive isotopes of xenon of atomic weight from 131 to 145 are formed; of these, the most harmful for reactor operation is the isotope of atomic weight 135, which is a strong absorber of thermal neutrons. As this isotope accumulates in the fission products it "poisons" the reactor to such an extent that the fuel elements have to be replaced long before uranium-235 burns out completely.
In nature, xenon is formed as a result of spontaneous disintegration of uranium-238 and uranium-235 contained in minerals. Knowing the half-life of uranium-235 (1.9×10^{17} years) and that of uranium-238 (0.8×10^{16} years) and fin-

ding the xenon/uranium weight ratio, one can calculate the absolute age of a uranium-containing mineral.

X-rays (Röntgen rays). Electromagnetic radiation of very short wavelength—about 0.06 to 20 A (one angström = 10^{-8} cm). X-rays are emitted on slowing-down of a flux of fast neutrons in a substance (see *Bremsstrahlung*). Here, a continuous spectrum of X-rays may be formed—from the shortest to the longest wavelengths, although the wavelength of most of the rays emitted by the substance will be the shorter, the higher is the energy (velocity) of the electrons bombarding it. When the electron energy is so high that it makes electrons located in the innermost shells shift from one orbit to another, so-called *characteristic rays* are emitted which have a linear rather than a continuous spectrum.

This phenomenon makes it possible to determine a number of physical properties and details of the structure of a substance from the spectrum of X-rays emitted by it on irradiation with a fast-neutron flux.

Y

"Yellow speck". In contrast to such metals as gold or platinum, uranium is not encountered in nature in pure form, although it is among the most abundant chemical elements in the earth's crust (0.0005 per cent, same as lead). It is very widely distributed and only in extremely

rare cases forms ore bodies of commercial value (usually not more than 2 per cent).

Uranium is found in very many minerals: sandstones, schists, quartz conglomerates, gravel, granites, pegmatites, phosphates, lignites, and others, mostly as uranous-uranic oxide (uranyl-uranate) U_3O_8, which miners commonly call "yellow speck".

According to the calculations of the International Atomic Energy Agency, by 1980 the demand for this material in the whole world will rise to about 550,000 tons, and by the year 2,000 to 3,500,000 tons, whereas its production at the end of 1968 was only 400,000 tons. Since the known reserves of it are at present 700,000 to 826,000 tons, scientists have to think of maintaining the balance of reserves. Therefore, by 1980 the geological and mining industry will have to discover, estimate and explore deposits of lean ores containing about one million tons of U_3O_8, which could be profitably exploited.

Yield, fission (see *Uranium fission products*). When a certain amount of nuclear fuel (uranium-235, plutonium-239, etc.) is fissioned in the course of a nuclear reaction, about the same amount of radioactive isotopes of elements whose masses range from 72 to 164 is formed. Part of them disintegrate very rapidly, transforming ultimately into stable isotopes of other elements. Only a comparatively small number of long-lived radioactive isotopes remain in any appreciable amounts (up to 5-7 per cent). These are strontium-90 (5.3%), zirconium-97 (6.4%), technetium-99 (6.2%), cesium-137 (6.2%), krypton-91 (6.0%); they emit various kinds of radiation (gamma- and beta-rays) and have different half-lives.

Z

Zeeman effect. A splitting of spectral lines when the light source being studied is placed in a magnetic field. First discovered by P. Zeeman in 1896, the Zeeman effect furnishes information of prime importance in the analysis of spectra It allows an evaluation of the ratio of charge to mass of the electron and an evaluation of its precise magnetic moment.

Zirconium, Zr. A metallic element, atomic number 40, atomic weight 91.22 (natural isotopes 90, 91, 92, 94, 96). Zirconium is one of the more abundant elements, and it is distributed widely in the earth's crust. Because of the very reactive nature of the metal it is found only in the combined state.

Zirconium is an important nuclear material. It is used in nuclear reactors as a structural and container material because of its low neutron-absorption cross section (when free of hafnium), its exceptional corrosion resistance, and its mechanical strength.